NSUF ION BEAM INVESTMENT OPTIONS WORKSHOP

INL Meeting Center, Energy Innovation Laboratory

March 22-24, 2016







DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

NSUF Ion Beam Investment Options Workshop

March 22-24, 2016

INL Meeting Center, Energy Innovation Laboratory

Idaho National Laboratory Nuclear Science User Facilities Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

NSUF Ion Beam Investment Options Workshop

March 22-24, 2016

INL Meeting Center, Energy Innovation Laboratory

INL/EXT-16-37857

Approved	by:
----------	-----

Brenden Heidrich NSUF Capability Scientist

J. Rory Kennedy

Director, NSUF

20 JUN 2016

Date

120/20

CONTENTS

ACF	RONYMS	vii
1.	INTRODUCTION	1
2.	WORKSHOP PARTICIPANTS	1
3.	WORKSHOP STRUCTURE AND PROCESS FLOW	3
4.	CRITERIA SELECTION AND WEIGHTING	
5.	ION BEAM FACILITY ASSESSMENT	10
6.	FUTURE WORK	12
7.	REFERENCES	12
App	endix A — Workshop Agenda	13
App	endix B — NSUF Presentations (Workshop and Criteria Weighting)	19
	Welcome Presentation	21
	Comments from the Introduction to ThinkTank Exercise	27
	Workshop Criteria Presentation 1	28
	Workshop Criteria Presentation 2	
	Workshop Criteria Presentation 3	
App	endix C — Criteria Weighting Data and Comments	53
	Criteria Weighting – Exercise 1 (pre-workshop exercise)	55
	Community Comments on the Criteria (#2)	56
	Criteria Weighting – Exercise 3	57
	Community Comments on the Criteria (#3)	
App	endix D — Ion Beam Users Presentations	61
	Presentation: NSUF User's Organization	63
	Presentation: Irradiation Material Testing	72
	Presentation: LWRS Program Data Needs	84
	Presentation: Nuclear Energy Advanced Modeling	89
	Presentation: Fuel Cycle R&D	99
	Presentation: Used Fuel Disposition	108
	Presentation: EPRI	116
App	endix E — Ion Beam Facility Presentations	
	Presentation: IVEM-Tandem User Facility	125
	Presentation: Extreme Materials Beam Line	137

Presentation: Capabilities at the Idaho Accelerator	148
Presentation: CMUXE, Purdue University	160
Presentation: High-energy Ion Implantation Capability at LLNL	175
Presentation: Wisconsin IBL	184
Presentation: In situ Ion Irradiation Transmission	191
Presentation: Michigan IBL	202
Presentation: Accelerator Based Facility for Materials Irradiation Testing	220
Presentation: In-Situ X-ray Characterization of Microstructural Evolution	231
Presentation: Univ. of Tennessee IBML	242
Presentation: Edwards Accelerator Laboratory at the University of Ohio	253
Presentation: Ion Beam Laboratory at Texas A&M University	264
Presentation: IBML at LANL	277
Presentation: Potential for Laboratory Compact Cyclotrons	292
Appendix F — Facility Ranking Exercise	
Appendix G — Ion Beam Facilities' Quantitative Data	319
FIGURES	
Figure 1. Relative weights of the 10 final criteria and their standard deviations $(\pm 1\sigma)$	8
Figure 2. Distribution of votes for criteria weighting exercise.	9
Figure 3. Overall score and ranking of the ion beam facilities.	11
TABLES	
Table 1. Workshop participants.	1
Table 2. Original 25 criteria and weights	4
Table 3. Original 25 criteria combined into eight	5
Table 4. Final 10 criteria used in the NSUF workshop to assess ion beam facilities	

ACRONYMS

AEC	A	0.4.00	
AEC	Atomic Energy Commission	CASS	cast austenitic stainless steel
AFC	Advanced Fuel Campaign	CEA	Commissariat à l'Energie Atomique
AFM	atomic force microscopy	CLIM	Characterization Laboratory for
AGR	advanced gas-cooled reactor		Irradiated Materials
ALARA	as low as reasonably achievable	CMUXE	Center for Materials under Extreme Environment
AMS	accelerator mass spectrometry	CSTAR	Center for Science and Technology
ANL	Argonne National Laboratory		with Accelerators and Radiation
ANS	American Nuclear Society	CT	computed tomography
APS	Advanced Photon Source	DBTT	ductile-brittle transition temperature
ARRM	Advanced Radiation-Resistant Material	depU	depleted uranium
A D.T.		DFT	density functional theory
ART	Advanced Reactor Technologies	DoD	U.S. Department of Defense
ATLAS	Argonne Tandem-Linac Accelerator System	DOE	U.S. Department of Energy
ATR	Advanced Test Reactor	DOE-BER	U.S. Department of Energy Biological and Environmental
AUGER	auger electron spectroscopy		Research
BAM	Federal Institute for Materials Research and Testing (Germany)	DOE-IRP	U.S. Department of Energy Integrated Research Projects
BCC	body-centered cubic	DOE-NE	U.S. Department of Energy Office
BLAIRR	Brookhaven Linear Accelerator		of Nuclear Energy
	IRRadiation Test Facility	DOT	U.S. Department of Transportation
BLIP	Brookhaven Linear Isotope	dpa	displacements per atom
DVG	Producer	DR	direct reading
BNC	Birck Nanotechnology Center	DTA	differential thermal analysis
BNL	Brookhaven National Laboratory	DuET	Dual-Beam Facility for Energy
BR2	Belgian Reactor 2		Science and Technology
BSD	backscattered electron detector	EAF	environmentally assisted fatigue
BSU	Boise State University	EBIC	electron beam induced current
BU	burn-up	EBSD	electron backscatter diffraction
BWR	boiling water reactor	EDS	energy dispersive spectroscopy
CAES	Center for Advance Energy Studies	EMC	Electron Microscopy Center
CAMS	Center for Accelerator Mass	EPRI	Electric Power Research Institute
	Spectrometry	ERD	elastic recoil detection
CASL	Consortium for Advanced Simulation of Light Water Reactors	ERDA	Energy Research and Development Administration

EUPS	extreme ultraviolet photoelectron spectroscopy	IBA	ion beam analysis
FCCI	fuel cladding chemical interaction	IBIOW	Ion Beam Investment Options Workshop
FCM	fully ceramic microencapsulated	IEE	insulator enhanced etch
FCRD	Fuel Cycle Research and	IMBL	Ion Beam Materials Laboratory
FEG	Development field emission gun	IMPACT	interaction of materials with particles and components testing
FEM	finite element analysis	IMT	ion microtomography
FFAG	fixed field alternating gradient	INL	Idaho National Laboratory
FG	fission gas	INPP	Institute of Nuclear and Particle
FHR	fluoride-salt-cooled high-		Physics
	temperature reactor	IR	infrared
FIB	focused ion beam	IRP	Integrated Research Project
FMI	fuel matrix interaction	ISU	Idaho State University
GAIN	Gateway for Accelerated Innovation in Nuclear	IVEM	intermediate-voltage electron microscope
GB	grain boundary	IXB	ion x-ray beam
GISAXS	grazing incidence small-angle x-ray	KMC	kinetic Monte Carlo
	scattering	LANL	Los Alamos National Laboratory
GIXRD	grazing incidence x-ray diffraction	LANSCE	Los Alamos Neutron Science Center
HAADF	high-angle annular dark field detector	LBE	lead-bismuth eutectic
HEDM	high energy diffraction microscopy	LE	low energy
HEDP	high-energy density physics	LEAP	local electrode atom probe
HEU	highly enriched uranium	LEISS	low-energy ion scattering spectroscopy
HFIR	High-Flux Isotope Reactor	LEU	low enriched uranium
HLW	high-level waste	LINAC	linear accelerator
HREM	high-resolution episcopic microscopy	LLNL	Lawrence Livermore National Laboratory
HRTEM	high-resolution transmission electron microscopy	LMIG	Laser Material Interaction Group
НТ	high temperature	LN	liquid nitrogen
HVEM	high-voltage electron microscope	LP	low pressure
HXN	hard x-ray nanoprobe	LPP	laser-produced plasma
I3TEM	in situ ion irradiation transmission	LT	low temperature
17 1 1711	electron microscope	LWR	light-water reactor
IASCC	irradiation-assisted stress corrosion cracking	LWRS	light-water reactor sustainability

MAaD	Materials Aging and Degradation	ODS	oxide dispersion strengthened
MBC	Multi-Beam Chamber	ORNL	Oak Ridge National Laboratory
MC	Monte Carlo	PHENIX	Pioneering High Energy Nuclear
MD	molecular dynamics		Interaction Experiment
MIBL	Michigan Ion Beam Laboratory	PID	photoionization detector
MIT	Massachusetts Institute of	PIE	post-irradiation examination
	Technology	PIXE	proton induced x-ray emission
MITR	Massachusetts Institute of	PKA	primary knock-on atom
MCE	Technology Reactor	PNNL	Pacific Northwest National
MSE	materials science and engineering	DD II AE	Laboratory
MTR	materials test reactor	PRIME	particle radiation interaction with matter experiments
NASA	National Aeronautics and Space Administration	PWR	pressurized water reactor
natU	natural uranium	PWSCC	primary water stress corrosion
NC	nanocolumnar		cracking
NDE	nondestructive examination	QA	quality assurance
NDMAS	Nuclear Data Management and	QCM	quartz crystal microbalance
	Analysis System	R&D	research and development
NEAMS	Nuclear Energy Advanced Modeling and Simulation	RBS	Rutherford backscattering spectrometry
NEC	National Electrostatics Corporation	RD&D	research, development, and
NEET	Nuclear Energy Enabling Technology	RERTR	demonstration Reduced Enrichment for Research
NEID	Nuclear Energy Infrastructure		Test Reactors
	Database	RF	radio frequency
NEUP	Nuclear Energy University Program	RFI	request for information
NGNP	Next Generation Nuclear Plant	RHIC	Relativistic Heavy Ion Collider
NIH	National Institutes of Health	RIAM	risk-informed asset management
NNSA	National Nuclear Security Administration	RIP	radiation-induced phasing
NP	nanoparticulate	RISE	Research and Innovation in Science and Engineering
NRA	nuclear reaction analysis	RPV	reactor pressure vessel
NRC	U.S. Nuclear Regulatory	RT	room temperature
	Commission	RTE	rapid turnaround experiment
NSF	National Science Foundation	SANS	small-angle neutron scattering
NSLS	National Synchrotron Light Source	SAXS	small angle x-ray scattering
NSUF	Nuclear Science User Facilities	SCC	stress corrosion cracking
		500	50055 COTTOSION CLACKING

SEM	scanning electron microscope	UCB	University of California at Berkeley
SLIA	Spiral Line Induction Accelerator	UCSB	University of California at Santa
SNF	spent nuclear fuel		Barbara
SNICS	source of negative ions by cesium	UFD	used fuel disposition
	sputtering	UHFI	ultra-high-flux irradiation
SS	stainless steel	UHV	ultra-high vacuum
SSD	silicon drift detector	UM	University of Michigan
STAR	Solenoidal Tracker at RHIC	UNF	used nuclear fuel
STEM	scanning transmission electron	UNT	University of North Texas
	microscope	UPS	ultraviolet photoelectron
STM	scanning tunneling microscopy		spectroscopy
STP	standard temperature and pressure	UT	University of Tennessee
SUNY	State University of New York	UW	University of Wisconsin
SUSNAG	Surface Science and Nanostructures	V&V	verification and validation
	Group	VCU	Virginia Commonwealth University
TAMU	Texas A&M University	VHTR	very high temperature reactor
TC	temperature calibration	WAXS	wide-angle x-ray scattering
TDS	thermal desorption spectroscopy	WEC	Westinghouse Electric Company
TEM	transmission electron microscopy	WNR	weapons neutron research
TGA	Thermogravimetric analysis	XFEL	x-ray free electron laser
TORVIS	toroidal volume ion source	XMAT	extreme materials beam line
TREAT	Transient Reactor Test Facility	XPD	x-ray powder diffraction
TRU	transuranic	XPS	x-ray photoelectron spectroscopy
TUF	tandem user facility	XRD	
UC	University of Colorado	ΛΝ	x-ray diffraction
	•		

NSUF Ion Beam Investment Options Workshop

1. INTRODUCTION

The Nuclear Science User Facilities (NSUF) Ion Beam Investment Options Workshop (IBIOW) was held to develop a set of recommendations (i.e., a priority list) for funding domestic ion beam irradiation capabilities available to researchers. These capabilities are focused on the support of nuclear-energy research, development, and deployment. The recommendations are intended for use by the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) when faced with decisions about investments in ion beam support, instruments, and facilities. Recommendations developed during the IBIOW are provided in the Supplement to the NSUF Ion Beam Investment Options Report: Initial Results and Recommendations (Heidrich 2016).

As part of their initial discussions of potential future funding, IBIOW participants considered input submitted through DOE-NE Request for Information DE-SOL-0008318, "University, National Laboratory, Industry and International Input on Potential Office of Nuclear Energy Infrastructure Investments (April 13, 2015)." Discussions and presentations of other input, whether specific or general in scope, were also welcomed. Also included was user input, including input regarding DOE-NE program interests and ion irradiation research, development, and deployment needs.

The workshop was held March 22–24, 2016, at the Idaho National Laboratory (INL) Meeting Center in the Energy Innovation Laboratory in Idaho Falls, Idaho. The workshop agenda is included in Appendix A.

2. WORKSHOP PARTICIPANTS

Workshop participants were selected from various sources, i.e., request-for-information respondents, Nuclear Energy University Program/Nuclear Energy Enabling Technology infrastructure applicants, universities with known expertise in nuclear engineering and materials science, and other developed sources.

Thirty-three members of the ion beam community attended the workshop, including 15 representatives of ion beam facilities, six representatives of DOE-NE research and development (R&D) programs, an industry representative from the Electric Power Research Institute, and the chairs of the NSUF User's Organization and the NSUF Scientific Review Board. Four ion beam users attended as advisors to the process but did not participate in the options assessment. Three members of the sponsoring agency, the Office of Science and Technology Innovation (NE-4), also attended the workshop.

Table 1 lists the workshop participants.

Table 1. Workshop participants.

radic 1. Workshop participants.			
Name	Organization/Position		
Workshop Organizers and Sponsors			
Rory Kennedy	Director, NSUF		
Brenden Heidrich	NSUF Capability Scientist		
Jodi Grgich	INL Facilitator		
Jody Henley	INL Facilitator		
Michael Worley	DOE-NE		
Thomas Miller	DOE-NE		
Alison Hahn	DOE-NE		

Table 1. (continued).

Name	Organization/Position
User Community Repres	
Sean McDeavitt	Texas A&M University – NSUF Scientific Review Board
Peng Xu	NSUF User's Organization Chair – Westinghouse
William Windes	Advanced Reactor Technologies (ART)
Sebastien Teysseyre	Light-Water Reactor Sustainability (LWRS)
Daniel Schwen	Nuclear Energy Advanced Modeling and Simulation (NEAMS)
Shannon Bragg-Sitton	Fuel Cycle Research and Development (FCRD)
Remi Dingreville	Used Fuel Disposition Program
Dean Peterman	Waste Forms Research and Development Program
Tiangan Lian	Electric Power Research Institute – Program Manager
Robert Odette	University of California – Santa Barbara
James Stubbins	University of Illinois – Urbana-Champaign
Ion Beam Facility Repre	
Abdellatif Yacout	Argonne National Laboratory (ANL) – Extreme Materials Beam Line (XMAT)
Meimei Li	ANL – Intermediate Voltage Electron Microscope (IVEM)
Nick Simos	Brookhaven National Laboratory (BNL) – Brookhaven Linear Isotope Producer (BLIP) – Brookhaven Linear Accelerator IRRadiation Test Facility (BLAIRR)
Lynne E. Ecker	BNL – Ion X-Ray Beam (IXB)
Jon L. Stoner	Idaho State University – Idaho Accelerator Facility
Yong Q. Wang	Los Alamos National Laboratory (LANL) – Ion Beam Materials Laboratory
Scott J. Tumey	LLNL – Center for Accelerator Mass Spectrometry
Lance Snead	Massachusetts Institute of Technology (MIT) – Nuclear Materials Laboratory
Steve Grimes	Ohio University – Edwards Accelerator Laboratory
Jitendra Kumar Tripathi	Purdue University – Center for Materials under Extreme Environment (CMUXE) Facility
Khalid Hattar	Sandia National Laboratories – In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
Lin Shao	Texas A&M University – Ion Beam Laboratory
Gary S. Was	University of Michigan – Ion Beam Laboratory
William J. Weber	University of Tennessee – Ion Beam Materials Laboratory
Beata Tyburska-Pueschel	University of Wisconsin – Ion Beam Laboratory

3. WORKSHOP STRUCTURE AND PROCESS FLOW

The NSUF IBIOW process began in December 2015 by soliciting interest in participating in the workshop from the various U.S. ion beam facility owners (universities and national laboratories). This was followed in January and February 2016 by official invitations to the workshop. The participants were asked to become involved in an ongoing process to define and weight criteria that could be used to judge the options available to DOE-NE to support and expand domestic ion beam irradiation capabilities. The assessment process started informally but later transitioned to the ThinkTank collaboration software.

Because the goal of the workshop was to provide recommendations to DOE-NE, a data-driven process was designed with the assistance of the INL's systems engineering division. ThinkTank collaborations software was selected as the tool to gather the data and link the workshop participants together. ThinkTank has been used successfully in a wide variety of government projects, notably the Nuclear Innovation Workshops held in March 2015.

The process outline was:

- 1. Select workshop participants
- 2. Determine and weight criteria (online, pre-workshop)
- 3. Hold the workshop (March 22–24, 2016)
 - a. Review the criteria list
 - i. Combine criteria (25 into 10)
 - ii. Reweight new combined criteria
 - b. View presentations by researchers (DOE-NE programs and ion beam users)
 - c. View presentations by ion beam facilities
 - d. Conduct an assessment and ranking exercise
 - e. Discuss future work
- 4. Analyze the workshop data, and generate a report

4. CRITERIA SELECTION AND WEIGHTING

The workshop participants generated and weighted a list of criteria against which to compare the various ion beam facilities and estimate the need for future investment. (Appendix B contains the information from the criteria exercises.) The original 15 criteria were generated by NSUF as a starting point for the discussion. Workshop participants then added criteria via email during the lead-up to the workshop. Table 2 shows the resulting 25 criteria and the weights assigned by the workshop participants using the ThinkTank software (before the workshop). The total list of 25 criteria proposed at the start of the workshop was too large to handle in the 3 days allotted for the workshop, so NSUF suggested eight combined criteria to replace the 25 original criteria (see Table 3). Appendix C provides criteria weighting data and comments.

Table 2. Original 25 criteria and weights.

	2. Original 23 Criteria and weights.		Std.
No.	Criteria	Mean	Dev.
1	Scientific merit and potential merit	8.60	1.35
2	Broad applicability (cross-cutting – i.e., multi-program)	7.07	2.25
3	International capabilities alternatives	4.80	1.90
4	DOE-NE programmatic mission need	7.80	1.82
5	Nuclear energy industry needs	6.13	2.67
6	Proportion of time to be allocated to direct DOE-NE mission work through Gateway for Accelerated Innovation in Nuclear [GAIN], NSUF, or DOE-NE programs	6.27	1.67
7	Current/past DOE-NE support/investment	5.93	1.94
8	Current DOE-NE work performed at facility	6.27	2.49
9	User experiment throughput capability	6.67	2.09
10	Beam energies (and energy ranges)	7.88	1.78
11	Ion types and variety	7.69	2.24
12	Variety of irradiation environments	7.44	2.03
13	Multiple analytical techniques available	5.75	2.67
14	Radiation levels allowed for samples	6.31	2.50
15	Multiple convergent beams (dual or triple)	6.50	2.31
16	Ability to match prototypic conditions	6.31	2.75
17	In situ examination during irradiation	6.56	2.92
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	5.63	2.42
19	Does the facility provide new capabilities?	6.14	3.37
20	Radiation effects/damage experience at the host institution	6.88	3.07
21	Need to define and have new capability be on path toward greater applicability and relevance	6.21	2.58
22	Relative R&D impact of utilizing direct simulants (i.e., swift heavy ion) or indirect simulants (i.e., light ions)	5.43	2.90
23	Applicability of results to development or data goals	5.36	3.54
24	Is there support of small specimen test technology?	5.50	3.25
25	Standards development, including temperature sensing	5.21	2.83

Table 3. Original 25 criteria combined into eight.

Original	rginal 25 criteria combined into eight.		Std.				Std.
No.	Criteria	Mean	Dev.	Combined	Combined Criteria	Mean	Dev.
1	Scientific merit and potential merit	8.6	1.4				
2	Broad applicability (cross-cutting – i.e., multiprogram)	7.1	2.3	C1 high scientific merit and the pote	Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry	7.4	2.2
4	DOE-NE programmatic mission need	7.8	1.8				
5	Nuclear energy industry needs	6.1	2.7				
10	Beam energies (and energy ranges)	7.9	1.8			7.4	2.2
11	Ion types and variety	7.7	2.2	$\begin{bmatrix} & & & & & & & & & & & & \\ & & & & & & $	C2 Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)		
15	Multiple convergent beams (dual or triple)	6.5	2.3	C2			
12	Variety of irradiation environments	7.4	2.0		Ability of the facility to provide a variety	6.9	2.4
16	Ability to match prototypic conditions	6.5	2.8	C3	of irradiation environments and conditions	0.9	2.4
13	Multiple analytical techniques available	5.8	2.7	C4	Ability of the facility to collect and analyze microstructural characterization data onsite and in situ	6.4	2.9
17	In situ examination during irradiation	6.6	2.9				
20	Radiation effects/damage experience at the host institution	6.9	3.1	C4			
6	Proportion of time to be allocated to direct DOE-NE mission work through GAIN, NSUF, or DOE-NE programs	6.3	1.7	C5	DOE-NE support and activities		2.0
7	Current/past DOE-NE support/investment	5.9	1.9		(performed and anticipated) at the facility		
8	Current DOE-NE work performed at facility	6.3	2.5				
9	User experiment throughput capability	6.7	2.1				
19	Does the facility provide new capabilities?	6.1	3.4		This are conclusive of the facility		
21	Need to define and have new capability be on path toward greater applicability and relevance	6.2	2.6	C6	Unique capabilities of the facility, including new technology	6.2	2.9

Table 3. (continued).

Original No.	Criteria	Mean	Std. Dev.	Combined	Combined Criteria	Mean	Std. Dev.	
14	Radiation levels allowed for samples	6.3	2.5					
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	5.6	2.4	C7	Ability of the facility to handle radioactive materials in the beams and elsewhere onsite	5.8	2.7	
24	Is there support of small specimen test technology?	5.5	3.3					
23	Applicability of results to development or data goals	5.4	3.5	G O	G0	Ability of the facility to produce high-quality data that can support	<i>r</i> 2	2.0
25	Standards development, including temperature sensing	5.2	2.8	C8	verification and validation of modeling and simulation	5.3	3.2	

The weights and standard deviations shown in Table 3 for the eight combined criteria are a combination of the standard deviations from the original 25 criteria. During the first day of the workshop, the eight criteria were expanded to the following nine combined criteria based on input from the participants:

- 1. Ability of the facility to produce results of high scientific merit and accurately simulate neutron irradiation results
- 2. Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)
- 3. Ability of the facility to provide a variety of irradiation environments and conditions
- 4. Ability of the facility to collect and analyze materials properties and perform microstructural characterization data onsite and/or in situ
- 5. DOE-NE support and activities (performed and anticipated) at the facility, including the volume of experiments that can be handled
- 6. Unique capabilities of the facility, including any new technology
- 7. Ability of the facility to handle radioactive materials in the beams and elsewhere onsite
- 8. Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation
- 9. Ability of the facility to produce results that meet the needs of DOE-NE (including cross-cutting programs) and the nuclear energy industry.

4.1 Final Criteria

After much discussion, a set of 10 criteria were agreed upon by the workshop participants. These criteria were discussed and weighted during the workshop. Table 4 shows the weights normalized so that the highest weight is equal to 100% and the remaining are relative to that one. The ThinkTank software also calculates the standard deviation of the weights based on the scores and the number of voters. Unfortunately, the spread in scores given by the participants was too large to use the weights in a statistically valid quantitative assessment. The relative weights $\pm 1\sigma$ are shown in Figure 1. The plot shows that there is significant overlap in the weights. Even with this issue, the relative importance of the criteria can be observed through the raw scores. The highest scoring criteria are generally also the ones with the least variation in opinion, as shown by the lower coefficient of variation (CoV) (standard deviation divided by the weight or percent standard deviation).

Table 4. Final 10 criteria used in the NSUF workshop to assess ion beam facilities.

#	Combined Criteria	Relative Weight	CoV
C1	Viability for the capability to extend our understanding towards accurately simulating nuclear irradiation conditions (neutrons or fission fragments).	100%	13%
C10	Ability of the facility to produce results that meet the needs of the DOE – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.	94%	21%
С3	Ability of the facility to provide a variety of well-controlled target environments and conditions.	92%	22%
C8	Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite.	89%	20%
C 5	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in-situ.	86%	24%
С9	Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.	86%	29%
C2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	85%	24%
С7	Unique capabilities of the facility including any new technology that has the capability to close technological gaps.	83%	30%
C6	Current or potential productivity of the facility (e.g. fewer high-impact experiments or high-volume sample throughput).	69%	35%
C4	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite.	62%	39%

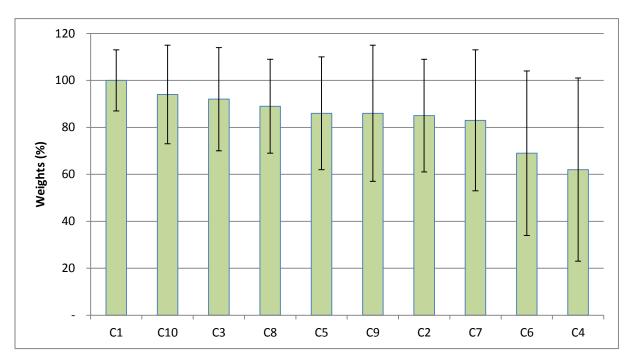


Figure 1. Relative weights of the 10 final criteria and their standard deviations ($\pm 1\sigma$).

Figure 2 shows the final 10 criteria and the proportion of votes to weight each one as high (dark green), medium (light green), or low (yellow). The value in parentheses is the relative weight of the criterion. Note that the final order of the facility rankings was not affected by the use or non-use of the weighting criteria.

The following pages show the data from the ThinkTank software, including the results from the weighting and the comments made by the workshop participants.

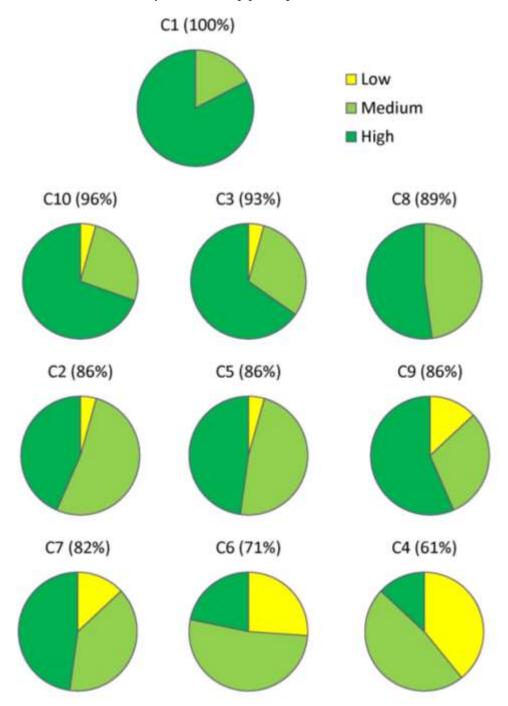


Figure 2. Distribution of votes for criteria weighting exercise.

5. ION BEAM FACILITY ASSESSMENT

In addition to developing and weighting criteria, workshop participants viewed presentations from ion beam users and DOE-NE R&D programs and then the ion-beam facility representatives. These presentations are provided in Appendixes D and E along with any community comments in the sidebar of the slides.

Following the presentations, the workshop participants assessed each ion beam facility against each of the final 10 criteria. This exercise was performed individually, although discussions and questions were allowed. ThinkTank software was used to collect the data from the assessments. The data and comments from the facility ranking exercise are in Appendix F. Figure 3 shows the results of the assessment of the facilities against the criteria. The absolute scores are slightly different if the criteria weights are applied, but the overall ranking does not change.

It should be noted that the facilities are not all focused on the same objectives and therefore may have significantly different designs. Of the 15 facilities that were reviewed, only 11 were operational at the time. Four facilities were proposed to be constructed in the future:

- 1. Argonne National Laboratory Extreme Materials Beam Line (XMAT)
- 2. Brookhaven National Laboratory (BNL) Ion X-Ray Beam (IXB)
- 3. BNL Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex BLIP-BLAIRR
- 4. Massachusetts Institute of Technology (MIT) MIT Nuclear Materials Laboratory.

Additionally, the facility at Purdue University focuses on surface science of materials and utilizes much lower energy ions than the others. The Edwards Accelerator Laboratory at The Ohio University is primarily engaged in nuclear data measurement and not in the irradiation effects on materials. The Idaho Accelerator Laboratory at Idaho State University is a multipurpose facility that supports a wide variety of research endeavors. These three facilities should not be judged in the same manner as the others.

Beyond this, the remaining eight currently operating facilities all provide vital support to nuclear materials researchers. The individual capabilities of these eight facilities differ based on their particular missions. Three facilities have (or will have soon) in situ characterization capabilities that combine ion irradiation with a transmission electron microscope. The proposed facilities seek to provide in situ characterization with an x-ray source.

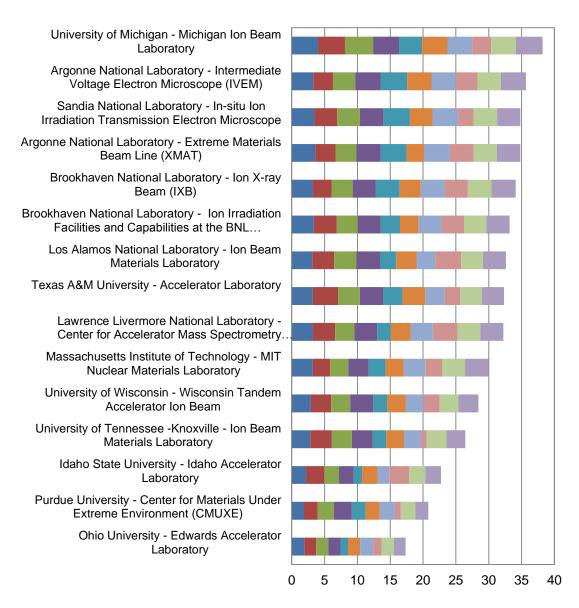


Figure 3. Overall score and ranking of the ion beam facilities.

- C1: Viability for the capability to extend our understanding towards accurately simulating nuclear irradiation conditions (neutrons or fission fragments).
- C2: Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.).
- C3: Ability of the facility to provide a variety of wellcontrolled target environments and conditions.
- C4: Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite.
- C5: Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in-situ.
- C6: Current or potential productivity of the facility (e.g. fewer high-impact experiments or high-volume sample throughput).
- C7: Unique capabilities of the facility including any new technology that has the capability to close technological gaps.
- C8: Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite.
- C9: Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.
- C10: Ability of the facility to produce results that meet the needs of the DOE – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.

6. FUTURE WORK

During the closeout discussion from the NSUF IBIOW, three criteria were viewed by the participants as being quantitative in nature and therefore better judged by direct comparison instead of peer assessment. These were Criteria C2, C3, and C8. NSUF gathered quantitative data for these three areas for use in future assessments. These data can be found in Appendix G.

The NSUF IBIOW is the first step in assessing and building a plan for the development and expansion of ion beam irradiation capabilities in the United States. The ThinkTank software can be used in the future to allow additional people, such as a wider community of ion beam users, to review the presentations and quantitative data and to participate in the assessment of the existing and proposed ion beam irradiation facilities. In addition, a road-mapping exercise is planned for Fiscal Year 2017 to layout the direction of R&D efforts.

7. REFERENCES

Heidrich, Brenden J., Supplement to the NSUF Ion Beam Investment Options Report: Initial Results and Recommendations, INL/LTD-16-38580, Rev. 0, April 2016.

Appendix A Workshop Agenda

Appendix A

Workshop Agenda

Tuesday, March 22

8:00	ThinkTank and INL Guest Network setup
8:30	Introductions of Workshop Participants (light breakfast)
9:00	Welcome, Introductions and Workshop Overview
9:10	Agenda and Conduct of Workshop
9:20	Introduction to ThinkTank
9:30	Discussion of the Workshop Analysis Criteria and Weights
10:30	Morning Break (30 min)
11:00	NSUF User's Organization
11:30	Irradiation Material Testing for VHTR Core Materials
12:00	
	Light Water Reactor Sustainability (LWRS) Program Data NeedsSebastien Teysseyre <i>Idaho National Laboratory Scientist</i>
12:30	
12:30 2:00	Idaho National Laboratory Scientist Lunch (90 min) Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program Data Needs
	Idaho National Laboratory Scientist Lunch (90 min) Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program Data

3:00	Afternoon Break (30 min)
3:30	The IVEM-Tandem User Facility: TEM with In-situ Ion IrradiationMeimei Li *Argonne National Laboratory Research Scientist*
4:00	Extreme Materials Beam Line
4:30	Capabilities at the Idaho Accelerator and RISE Research Centers at Idaho State University
5:00	Closing Discussion – Day 1
Wedn	esday, March 23
8:00	Advanced Materials Characterization at CMUXE, Purdue University Jitendra Kumar Tripathi Purdue University, Senior Research Associate
8:30	A High-Energy Ion Irradiation Capability for Radiation Damage Experiments at the LLNL Center for Accelerator Mass Spectrometry
9:00	Wisconsin Ion Beam Laboratory: Capabilities and NeedsBeata Tyburska-Pueschel University of Wisconsin Research Faculty
9:30	In-situ Ion Irradiation Transmission Electron Microscope at SNLKhalid Hattar Sandia National Laboratory Scientist
10:00	Morning Break (30 min)
10:30	Ion Irradiation Capabilities at the Michigan Ion Beam Laboratory
11:00	Accelerator Based Facility for Materials Irradiation Testing
11:30	In-situ X-ray Characterization of Microstructural Evolution due to Ion Beam Irradiation
12:00	University of Tennessee Ion Beam Materials Laboratory

12:30	Lunch (90 min)				
2:00	Edwards Accelerator Laboratory at the University of Ohio				
2:30	Ion Beam Laboratory at Texas A&M University				
3:00	Ion Beam Materials Laboratory				
3:30	Afternoon Break (30 min)				
4:00	U.S. Nuclear Industry User Community Requirements				
4:30	Potential for Lab Compact Cyclotrons: Ions at Energies Relevant to Engineering Properties				
5:00	Closing Discussion - Day 2				
Thursday, March 24					
8:00	Discussion of Final Criteria and Weighting ExerciseBrenden Heidrich/Jody Henley INL Facilitator				
9:30	Ranking Exercise for Investment Options				
10:00	Analysis of Results and Discussion				
11:00	Workshop Closeout				

Appendix B

NSUF Presentations (Workshop and Criteria Weighting)

Appendix B

NSUF Presentations (Workshop and Criteria Weighting)

This appendix provides NSUF presentations made at the workshop with comments from workshop participants (in the sidebar).

Welcome Presentation

Brenden Heidrich

Nuclear Science user Facilities — Ion Beam Investment Options Workshop – Brenden Heidrich R&D Capability Scientist – NSUF Ion Beam Investment Workshop Idaho National Laboratory Idaho Falls, ID March 22, 2016



Nuclear Science User Facilities

Nuclear Energy

Nuclear Science User Facilities

Ion Beam Investment Options Workshop

Brenden Heidrich

R&D Capability Scientist

NSUF Ion Beam Investment Workshop
Idaho National Laboratory
Idaho Falls, ID
March 22, 2016

INL/MIS-16-37818

Safety Briefing



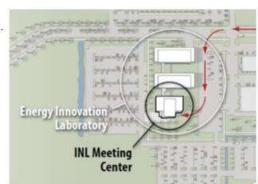
Nuclear Energy

Safety Briefing



In case of emergency, exit through the south or west doors.

- The assembly area is in the west parking lot towards CAES.
- Please don't try to drive away, it interferes with emergency vehicles.
- No eating or drinking during an emergency situation.
- · Restrooms are in the lobby.
- . Do not try to enter EIL Bldg. B.
- Smoking areas are outside to the west, 25 ft from the entrances.



2

Nuclear Science User Facilities — Ion Beam Investment Options Workshop – Brenden Heidrich R&D Capability Scientist – NSUF Ion Beam Investment Workshop Idaho National Laboratory Idaho Falls, ID March 22, 2016



Nuclear Energy

Meeting Conduct



■ The meeting is being run by professional INL facilitators:

- · Jodi Grgich and Jody Henley.
- · They will be running the ThinkTank software in real-time.
- · Presentation time limits are:
 - 20 minutes for the presentation.
 - 10 minutes for questions and comments.

■ There are a few additional people participating over the Bluejeans conferencing system.

- · Audio only + ThinkTank
- · Audio is fed through the mics in the meeting rooms.
- Please limit the amount of non-meeting work on laptops and phones during the actual meeting.

3

Workshop Agenda



Workshop Agenda



Nuclear Energy

■ Tuesday

- 08:00 to 10:30 Workshop Setup & Organization
- 11:00 to 12:30 Ion Beam Users (part 1)
- 14:00 to 15:00 Ion Beam Users (part 2)
- 15:30 to 17:00 Ion Beam Facilities (part 1)

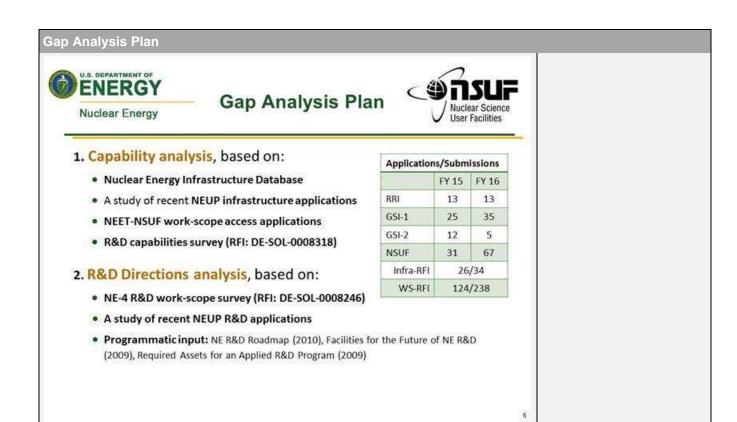
■ Wednesday

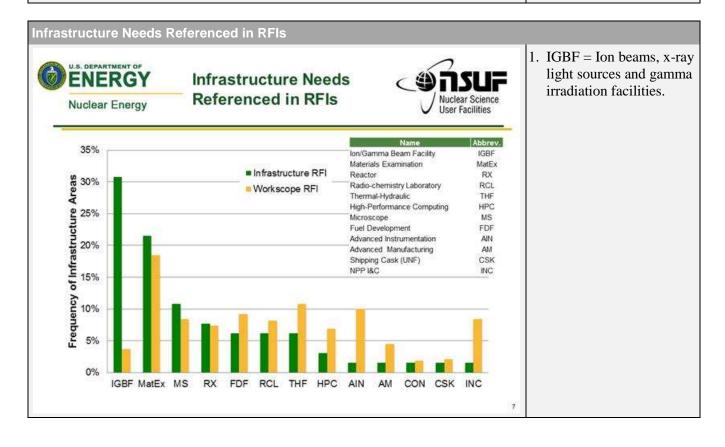
- 08:00 to 12:30 Ion Beam Facilities (part 3)
- 14:00 to 16:30 Ion Beam Facilities (part 4)
- 16:30 to 17:00 Nuclear Industry Requirements

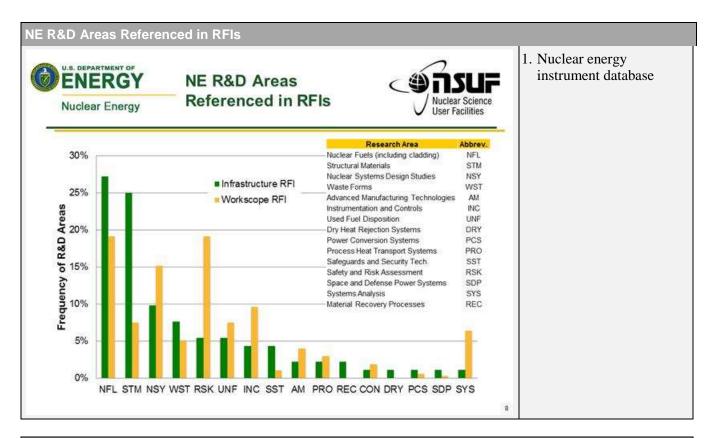
■ Thursday

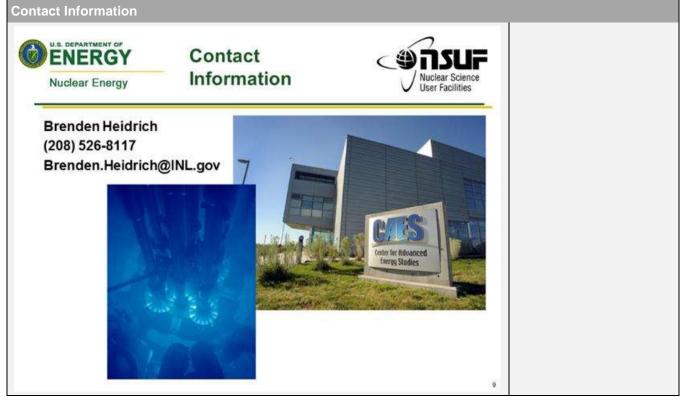
- 08:00 to 09:15 Final Criteria Discussion and Weighting
- 09:30 to 10:45 Ranking Exercise for Investment Options
- 11:00 to 12:30 Analysis of Results and Discussion
- 12:30 to 13:00 Establishment of Priority Lists

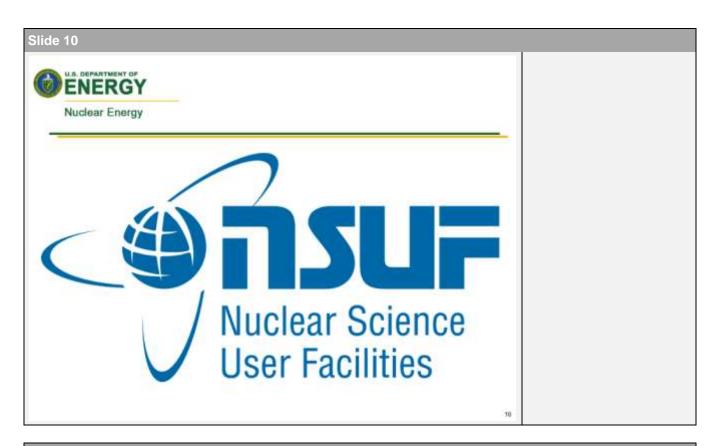
Infrastructure Management Program **ENERGY** Infrastructure **Management Program Nuclear Energy** 1. Gather Data on Nuclear Energy R&D Capabilities 2. Estimate Near, Mid and Long-term R&D Directions NEID 3. Use these to perform gap analyses for Nuclear Energy R&D. 4. Assist funding decisions and incorporate the results into the NEID.











DISCLAIMER



Nuclear Energy

DISCLAIMER

- This information was prepared as an account of work sponsored by an agency of the U.S. Government.
- Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.
- References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof.
- The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

1. It would be informative to map the allocation of infrastructure resources onto the infrastructure needs by category. That is, are resources being allocated according to needs or is some other criterion being used?

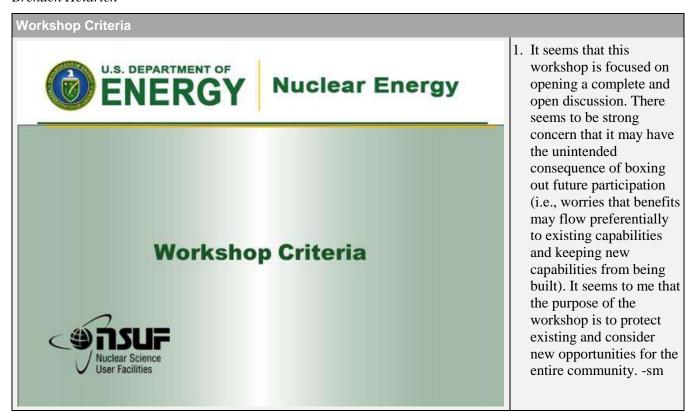
INL/MIS-16-37818

Comments from the Introduction to ThinkTank Exercise

- 1. To produce heavy damage in a short time.
 - 1.1 Is this equivalent to neutron damage?
 - 1.2 This is connected to neutron damage in some cases and not in others.
- 2. Fast, low, or no activation, relatively inexpensive.
- 3. Quantifiable well-defined damage.
- 4. To emulate neutron irradiation under various conditions.
- 5. Economical, quick method to implement radiation damage on materials.
 - 5.1 Large accelerators are not very economical
- 6. Dedicated compact accelerators are affordable.
- 7. Very important for fundamental research.
- 8. Ion beams can create damage that is similar to neutrons in certain situations at a much higher damage rate.
- 9. One important and realistic way to speed up materials screening.
- 10. Simulation of radiation damage in materials.
- 11. Offer surrogate irradiation to neutron damage.
- 12. To perform complex material property measurements unavailable to materials test reactor studies.
- 13. For creating far-from-equilibrium microstructures.
- 14. They are the only way to access the high damage rates in both light-water reactor and advanced reactor systems in reasonable times and at reasonable costs.
- 15. Ion beams allow for separation and control of a wide range of experimental conditions that facilitate the isolation and study of fundamental unit mechanisms that occur by radiation damage.
- 16. Simulate primary knock-on atoms from neutrons, fission fragments, and energetic particles from alpha and beta decay. Produce damage under controlled conditions on laboratory time scales.
- 17. To provide an initial look into the microstructure damage before spending the time and money on neutron irradiation.
- 18. Ion beams serve as surrogate for neutron, provide similar microstructure and effects as neutrons in much shorter time without introducing radioactivity.
- 19. Train students.
 - 19.1 This is important and often overlooked.
- 20. Provide data that are easier to use to develop models.
- 21. Separate effects studies.
 - 21.1 This is key to developing validated computational models.

Workshop Criteria Presentation 1

Brenden Heidrich



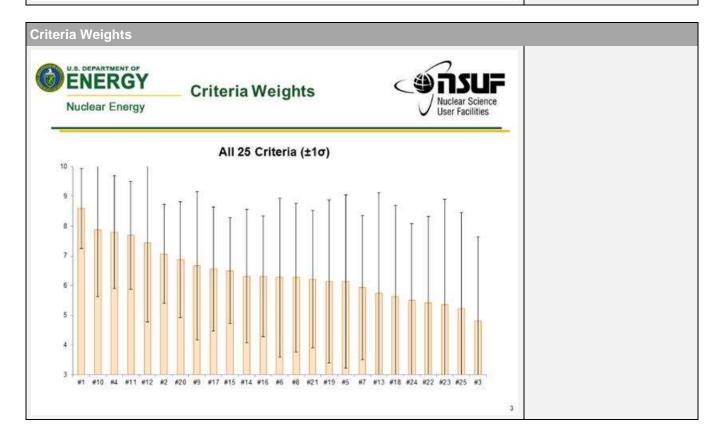
Original Criteria U.S. DEPARTMENT OF ENERGY Nuclear Energy Criteria 1 Scientific merit and potential merit 2 Broad applicability (cross-cutting-i.e. multi-program) 3 International capabilities alternatives 16 Ability to match prototypic

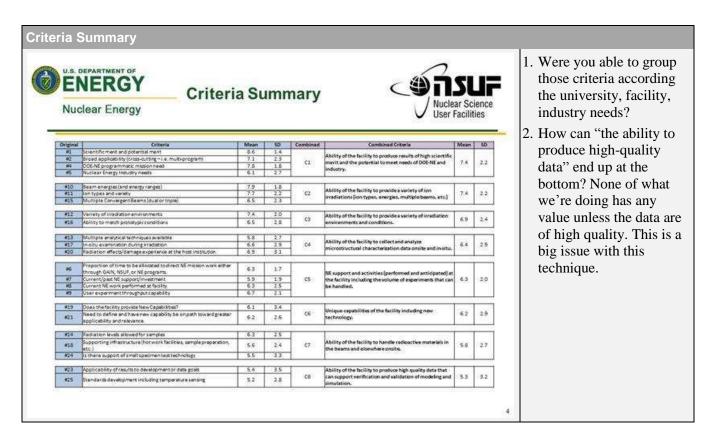
#	Criteria
1	Scientific merit and potential merit
2	Broad applicability (cross-cutting - i.e. multi-program)
3	International capabilities alternatives
4	DOE-NE programmatic mission need
5	Nuclear Energy Industry needs
6	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.
7	Current/past NE support/investment
8	Current NE work performed at facility
9	User experiment throughput capability
1 0	Beam energies (and energy ranges)
1	fon types and variety
1 2	Variety of irradiation environments
1 3	Multiple analytical techniques available

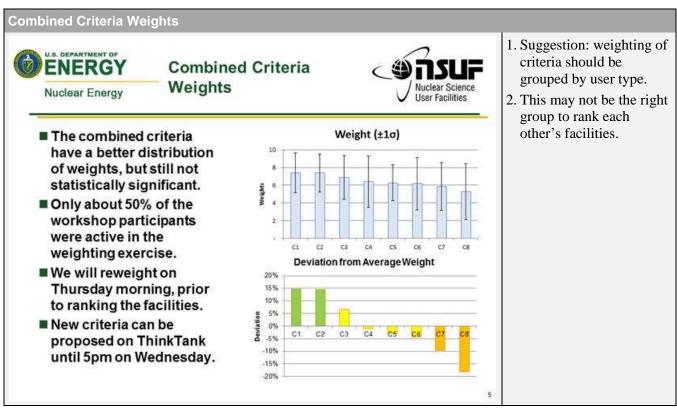
#	Criteria
14	Radiation levels allowed for samples
15	Multiple Convergent Beams (dual or triple)
16	Ability to match prototypic conditions
17	In-situ examination during irradiation
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)
19	Does the facility provide New Capabilities?
20	Radiation effects/damage experience at the host institution
21	Need to define and have new capability be on path toward greater applicability and relevance.
22	Relative R&D impact of utilizing direct simulants (i.e. Swift Heavy Ion) or indirect simulants (i.e. light ions.)
23	Applicability of results to development or data goals
24	Is there support of small specimen test technology
25	Standards development including temperature sensing

2

Nuclear Science User Facilities







C1: Scientific Merit



C1: Scientific Merit



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#1	Scientific merit and potential merit	0	0	0	0	1	0	1	4	5	4	8.6	1.4
#2	Broad applicability (cross-cutting – i.e. multi-program)	0	0	2	0	1	3	2	2	3	2	7.1	2.3
#4											3		1.8
#5	Nuclear Energy Industry needs	1	1	0	2	2	2	1	4	0	2	6.1	2.7

Combined Criterion	Mean	Std Dev
Ability of the facility to produce results of high		
scientific merit and the potential to meet needs of	7.4	2.2
DOE-NE and industry.	5831201	

- 1. Group #2, #4, and #5 together into a single criterion. Move #1 elsewhere and maybe revise.
- 2. #1 should be on its own or eliminated.
- 3. Interpreted this slide as the ability of the facility to analyze the beam data to simulate accurately neutron data from MTR studies. The combined criterion may need rewriting to address the issue of interpreting ion beam to neutron results.

- 6

C2: Variety of Irradiations



C2: Variety of Irradiations



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#10	Beam energies (and energy ranges)	0	0	1	0	1	0	2	6	4	2	7.9	1.8
#11	Ion types and variety	0	1	1	0	0	0	3	4	5	2	7.7	2.2
#15	Multiple Convergent Beams (dual or triple)	1	0	0	1	2	3	2	1	4	0	6.5	2.3

Combined Criteria	Mean	Std Dev
Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	7.4	2.2

- 1. Do convergent, multiple beams really fit with this criterion?
- 2. When it comes time to "vote" on how each facility capabilities are able to address individual criteria, I wonder if we should implement the "Russian Judge" model from Olympic sports and throw out the highest and lowest scores recorded (that may be unnecessary, but I thought I'd throw it out for consideration).
- 3. Beam energy is obviously important. I think the question is more "Cover beam energy spectrum from near surface to deeply penetrating ions."

C3 Irradiation Environments



C3: Irradiation **Environments**



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#12	Variety of irradiation environments	0	0	1	1	0	2	4	3	2	3	7.4	2.0
#16	Ability to match prototypic conditions	2	0	1	0	2	2	3	2	3	1	6.3	2.8

Combined Criteria	Mean	Std Dev
Ability of the facility to provide a variety of irradiation environments and conditions.	6.9	2.4

- 1. C2 and C3 might be combined
- 2. What is meant as irradiation environments and prototypic conditions (beta)? Could you be more specific?
- 3. Could move the multiple beams criterion here, as this describes the radiation environment.





C4: Microstructural Characterization **Nuclear Energy**



	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#13	Multiple analytical techniques available	1	1	2	C	4	2	2	0	3	1	5.8	2.7
#17	In-situ examination during irradiation	2	0	1	C	1	4	1	1	4	2	6.6	2.9
#20	Radiation effects/damage experience at the host institution	1	0	2	1	3	0	0	1	4	4	6.9	3.1

Combined Criteria	Mean	Std Dev
Ability of the facility to collect and analyze microstructural characterization data onsite and in-situ.	6.4	2.9

- 1. Do you mean in situ analytical techniques or available onsite for a subsequent analysis (beta)?
- 2. What is meant by damage experience? Do you want to know whether a facility has implantation and/or irradiation capability (beta)?
- 3. Consider adding material and bulk properties.
- 4. I would only consider that important only if I expect the facility to do characterization for me. Often characterization is done elsewhere and the facility only provides irradiation service.

C5: NE Support and Activities



Nuclear Energy

#7

#8

C5: NE Support and Activities

Criteria
Proportion of time to be allocated to direct NE mission

work either through GAIN, NSUF, or NE programs.

Current/past NE support/investment

Current NE work performed at facility

User experiment throughput capability



2.5

_	_	_	_	_			USGITA	GI
5	6	7	8	9	10	Mean	Std Dev	
4	3	2	2	2	0	6.3	1.7	
4	2	3	2	0	1	5.9	1.9	
=	-	_	•	_	-			

1234

0002

0021

Combined Criteria	Mean	Std Dev
NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.	6.3	2.0

- 1. Did DOE-NE weigh in on this one?
- 2. Isn't this the same as "Support DOE-NE missions" in C1? How is this different?

10

C6: Unique Capabilities



C6: Unique Capabilities



	Criteria	1	2	3 4	5	6	7	8 9	10	Mean	Std Dev
#19	Does the facility provide new capabilities?	3	0	1	1	1	1	3 2	2 2	6.1	3.4
#21	Need to define and have new capability be on path toward	1	0	2 (2	2	1	4	1 1	6.2	2.6

Combined Criteria	Mean	Std Dev
Unique capabilities of the facility including new technology.	6.2	2.9

- 1. What are the gaps within the current existing facilities?
- 2. Where do we ask the community about the interest/value of being able to test nuclear fuel?
- 3. New capabilities are only useful if they serve a purpose. So we need to make sure that this new capability will fill a gap.
- 4. Clarification: "new technology" covers everything.
- 5. New technology includes irradiation, characterization methods, etc.

1

C7: Radioactive Material Capabilities



C7: Radioactive Material Capabilities



1. C4 and C7 appear very similar. Not sure how they differ from each other?

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#14	Radiation levels allowed for samples	0	0	0	4	1	4	1	3	1	2	6.3	2.5
#18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	1	0	4	0	0	6	1	3	o	1	5.6	2.4
#24	Is there support of small specimen test technology	4	0	0	0	2	1	2	3	1	1	5.5	3.3

Combined Criteria	Mean	Std Dev
Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.	5.8	2.7

C8: High-Quality Data to Support Modeling and Simulation Efforts



Nuclear Energy

C8: High-Quality Data to Support Modeling and Simulation Efforts

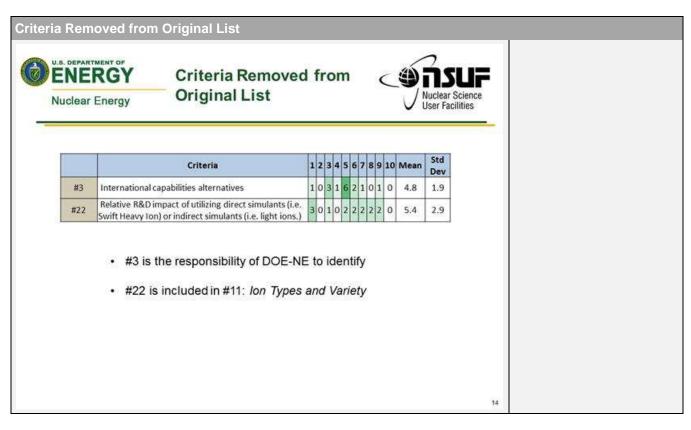


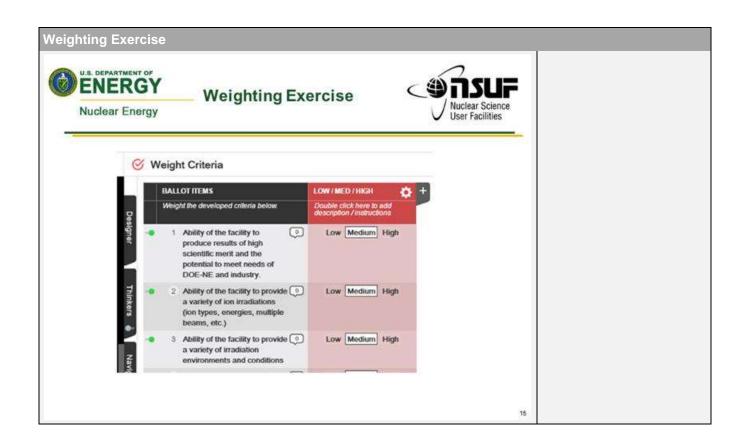
	ALCOHOLOGICA CONTRACTOR CONTRACTO	100	Н.	100		m	600		123	22		Mean	Std Dev
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5
#25	Standards development including temperature sensing	3	0	1	1	2	1	2	3	1	0	5.2	2.8

Combined Criteria	Mean	SD
Ability of the facility to produce high	PANE.	02202
quality data that can support verification	5.3	3.2
and validation of modeling and simulation.		

- 1. Combine #1 and #23 to form a new category.
- 2. I think we need to better define what is meant by high quality and what types of data are most important to the program.
- 3. I would remove "highquality data" from definition that can be confused with high-merit data and replace it with "Quality Data" to emphasize the QA aspect of the data rather than the merit.
- 4. Repeatability and reliability are important.
- 5. QA plan for data validation.
- 6. NQA-1?
- 7. Whether ion irradiation follows standard procedures is very important. The criteria should include repeatability and reliability.
- 8. I do not think ion irradiation data will ever be used for licensing.
- 9. For the past many years, the push for ion irradiation and computational materials science has been very active in leading into at least pre-licensing activities. It is not clear that this data will NEVER be used in that way. (But I agree that it's not likely, and at best it will not comprise the majority of the data generated.)

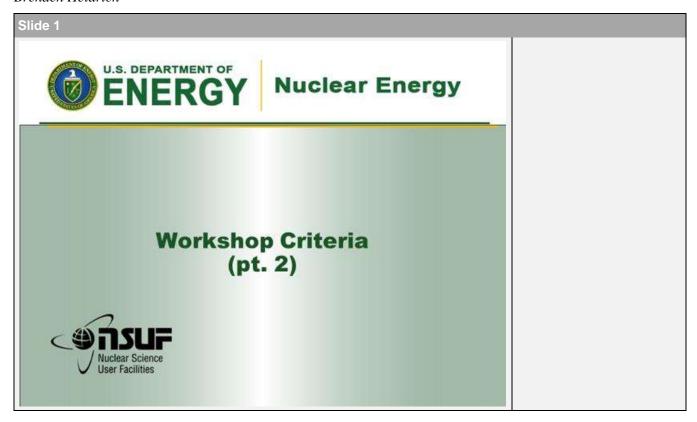
C8: High-Quality Data to Support Modeling and Simulation Efforts 10. User communitydefined standard methods and measurement techniques need to be developed with data validation with neutron irradiation damage before licensing actions could be considered based on ion beam irradiations alone. The roadmap for ion beams needs to be comprehensive if the licensing path is to be pursued.





Workshop Criteria Presentation 2

Brenden Heidrich



Original Criteria



Nuclear Energy

Original Criteria



1. Scientific knowledge and technical expertise to help with experimental design and execution.

#	Criteria
1	Scientific merit and potential merit
2	Broad applicability (cross-cutting - i.e. multi-program)
3	International capabilities alternatives
4	DOE-NE programmatic mission need
5	Nuclear Energy Industry needs
8	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.
7	Current/past NE support/investment
8	Current NE work performed at facility
9	User experiment throughput capability
1	Beam energies (and energy ranges)
1	lon types and variety
1 2	Variety of irradiation environments
1 3	Multiple analytical techniques available

#	Criteria
14	Radiation levels allowed for samples
15	Multiple Convergent Beams (dual or triple)
16	Ability to match prototypic conditions
17	In-situ examination during irradiation
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)
19	Does the facility provide New Capabilities?
20	Radiation effects/damage experience at the host institution
21	Need to define and have new capability be on path toward greater applicability and relevance.
22	Relative R&D impact of utilizing direct simulants (i.e. Swift Heavy Ion) or indirect simulants (i.e. light ions.)
23	Applicability of results to development or data goals
24	Is there support of small specimen test technology
25	Standards development including temperature sensing

New Criteria



New Criteria



Nuclear Energy

- Combined Criterion

 Ability of the facility to produce results of high scientific merit and accurately simulate neutron irradiation results.

 Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)

 Ability of the facility to provide a variety of irradiation environments and conditions.

 Ability of the facility to collect and analyze materials properties and perform microstructural characterization data onsite and/or in-situ.

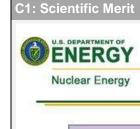
 DOE-NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.

 Unique capabilities of the facility including any new technology.

 Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.

 Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation

 Ability of the facility to produce results that meet the needs of the DOE Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.
- 1. Move #17 to C6.
- 2. Need to add a new criterion: technical support.
- 3. One strong need for DOE-NE will be to identify important criteria that are not well met by the existing infrastructure.
 Understanding gaps may lead to investment.
- 4. There is a strong push from individual groups to "protect their Wheaties." There is an appearance that these criteria are becoming a measure of quality on existing facilities with winners and losers emerging from this meeting. How can the discussion be transformed into a discriminating evaluation of facilities to discern what is available at each facility (and globally across the country) without creating the impression of "good/bad" grades?



C1: Scientific Merit



- 1. Suggestion: add "and simulate fission fragments."
- 2. Change to "simulate nuclear irradiation conditions."
- 3. Reword: Viability for the capability to extend our understanding toward accurately simulating neutron radiation results.
- 4. Rank to capability of the facility/team to answer the question: Can an ion beam simulate a neutron irradiation faster than a reactor can?

Combined Criterion

Ability of the facility to produce results of high scientific merit and accurately simulate neutron irradiation results.

			L		Į	0.0	J	Ш				Mean	Dev
#1	Scientific merit and potential merit	0	0	0	0	1	0	1	4	5	4	8.6	1.4
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5

C2: Variety of Irradiations



Nuclear Energy C2: Variety of Irradiations



Combined Criteria

Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)

An ideal facility should be able to cover the beam energy spectrum from near surface to deeply penetrating ions.

	Criteria		н									Mean	Std Dev
#10	Beam energies (and energy ranges)	0	0	1	0	1	0	2	6	4	2	7.9	1.8
#11	Ion types and variety	0	1	1	0	0	0	3	4	5	2	7.7	2.2
#15	Multiple Convergent Beams (dual or triple)	1	0	0	1	2	3	2	1	4	0	6.5	2.3

.

C3: Irradiation Environments



Nuclear Energy

C3: Irradiation Environments



- 1. Replace irradiation with "target."
- 2. Well controlled target conditions.

Combined Criteria

Ability of the facility to provide a variety of irradiation environments and conditions.

- Should this include multiple beamlines (instead of C2)?
- · Specific conditions:
 - · Temperature (heated and chilled)
 - · Chemical environments (water, LM, molten salts, etc.)
 - Pressure
 - · Other?

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#12	Variety of irradiation environments	0	0	1	1	0	2	4	3	2	3	7.4	2.0
#16	Ability to match prototypic conditions	2	0	1	0	2	2	3	2	3	1	6.3	2.8

C4: Materials Properties and Microstructural Characterization



Nuclear Energy

C4: Materials Properties and Microstructural Characterization



Combined Criteria

Ability of the facility to collect and analyze materials properties and perform microstructural characterization data onsite and/or in-situ.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#13	Multiple analytical techniques available	1	1	2	0	4	2	2	0	3	1	5.8	2.7
#17	In-situ examination during irradiation	2	0	1	0	1	4	1	1	4	2	6.6	2.9
#20	Radiation effects/damage experience at the host institution	1	0	2	1	3	0	0	1	4	4	6.9	3.1

- 1. Split into two criteria: onsite/in situ separate criteria.
- 2. There is a tradeoff between what can be done in situ vs. what can be done without that instrument on the target. Doesn't this capability have to be an add-on? All else being equal, does it also have in situ capability and/or micro structural characterization?

C5: NE Support and Activities



C5: NE Support and Activities Nuclear Energy



- 1. Replace volume with productivity (wordsmith).
- 2. Is this a question of how much work has been done at that site? If it is a projection of how much work will be done, doesn't it have to be based on capability, available time, and cost of the site?

Combined Criteria

DOE-NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.

	Criteria	88	8 10	188		89	1 3th	10	100	886	ROM.	Mean	Std Dev
#6	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.	0	0	0	2	4	3	2	2	2	0	6.3	1.7
#7	Current/past NE support/investment	0	0	2	1	4	2	3	2	0	1	5.9	1.9
#8	Current NE work performed at facility	1	1	0	0	4	1	2	4	1	1	6.3	2.5
#9	User experiment throughput capability	0	1	1	0	1	3	3	3	3	0	6.7	2.1

C6: Unique Capabilities



Nuclear Energy

C6: Unique Capabilities



Combined Criteria

Unique capabilities of the facility including any new technology.

· Does the capability fill any known gaps in technology?

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#19	Does the facility provide new capabilities?	3	0	1	0	1	1	1	3	2	2	6.1	3.4
#21	Need to define and have new capability be on path toward greater applicability and relevance.	1	0	2	0	2	2	1	4	1	1	6.2	2.6

- 1. Hard to do this unless you take a group of experts (users/modelers) and all the capabilities presented (or the experts from each place) and create a big matrix of available vs. what would be needed. If you don't, you get the problem of ranking wildly different technologies.
- 2. How far should we look into the past performance—

5, 10 years?

C7: Radioactive Material Capabilities



Nuclear Energy

C7: Radioactive Material



Combined Criteria

Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.

Radioactive structural materials

Fuel materials

- Surrogates
- depU or natU
- LEU or HEU
- Pu and actinides
- Highly-burned fuels

	Criteria	1	2	(1)	3	4 5	5	6	7	8	9	10	Mean	Std Dev
#14	Radiation levels allowed for samples	0	0	0	1	4	1	4	1	3	1	2	6.3	2.5
#18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	1	O	4		0 0	0	6	1	3	0	1	5.6	2.4
#24	Is there support of small specimen test technology	4	C	0)	0	2	1	2	3	1	1	5.5	3.3

10

C8: High-Quality Data to Support Modeling and Simulation Efforts



Nuclear Energy

C8: High-Quality Data to Support Modeling and Simulation Efforts



Combined Criteria

Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.

- · Facility should have a QA program (NQA-1 or equivalent).
- · Community standards should be developed and applied.
- Facility should follow standard procedures for irradiations, sample preparation, etc.

												Mean	Std Dev
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5
#25	Standards development including temperature sensing	3	0	1	1	2	1	2	3	1	0	5.2	2.8

C9: Meeting R&D Needs



Nuclear Energy

C9: Meeting R&D Needs

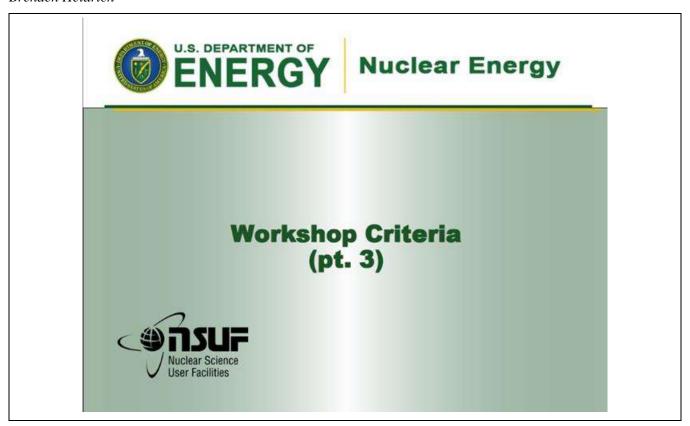


Combined Criterion

Ability of the facility to produce results that meet the needs of the Department of Energy – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#2	Broad applicability (cross-cutting – i.e. multi-program)	0	0	2	0	1	3	2	2	3	2	7.1	2.3
#4	DOE-NE programmatic mission need	0	0	0	1	1	1	3	3	3	3	7.8	1.8
#5	Nuclear Energy Industry needs	1	1	0	2	2	2	1	4	0	2	6.1	2.7

Workshop Criteria Presentation 3 *Brenden Heidrich*





Nuclear Energy

Final Edit



Combined Criteria Viability for the capability to extend our understanding towards accurately simulating nuclear C1 irradiation conditions (neutrons or fission fragments). Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.) Ability of the facility to provide a variety of well-controlled target environments and conditions. C3 Ability of the facility to collect and analyze materials properties and/or perform microstructural C4 characterization data onsite. Ability of the facility to collect and analyze materials properties and/or perform microstructural C5 characterization data in-situ. Current or potential productivity of the facility (e.g. fewer high-impact experiments or high-volume C6 sample throughput). Unique capabilities of the facility including any new technology that has the capability to close C7 technological gaps. Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams C8 and elsewhere onsite.



C10

validation of modeling and simulation.

(including cross-cutting programs) and the nuclear energy industry.

C1

Ability of the facility to produce quality-level data that can support licensing as well as verification and

Ability of the facility to produce results that meet the needs of the DOE - Office of Nuclear Energy



Viability for the capability to extend our understanding towards accurately simulating nuclear irradiation conditions (neutrons or fission fragments).

Combined Criterion

Ability of the facility to produce results of high scientific merit and accurately simulate neutron irradiation results.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#1	Scientific merit and potential merit	0	0	0	0	1	0	1	4	5	4	8.6	1.4
#23	Applicability of results to development or data goals	4	0	2	0	0	1	0	2	3	1	5.4	3.5



C2



Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)

Combined Criteria

Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)

An ideal facility should be able to cover the beam energy spectrum from near surface to deeply penetrating ions.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#10	Beam energies (and energy ranges)	0	0	1	0	1	0	2	6	4	2	7.9	1.8
#11	Ion types and variety	0	1	1	0	0	0	3	4	5	2	7.7	2.2
#15	Multiple Convergent Beams (dual or triple)	1	0	0	1	2	3	2	1	4	0	6.5	2.3

7



C3



Ability of the facility to provide a variety of well-controlled target environments and conditions.

Combined Criteria

Ability of the facility to provide a variety of irradiation environments and conditions.

Specific conditions:

- · Temperature (heated and chilled)
- · Chemical environments (water, LM, molten salts, etc.)
- Pressure
- · Other?

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#12	Variety of irradiation environments	0	0	1	1	0	2	4	3	2	3	7.4	2.0
#16	Ability to match prototypic conditions	2	0	1	0	2	2	3	2	3	1	6.3	2.8



C4 & C5



Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite.

Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in-situ.

	Combined Criteria
Ability	of the facility to collect and analyze materials properties and
perforn	n microstructural characterization data onsite and/or in-situ.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#13	Multiple analytical techniques available	1	1	2	0	4	2	2	0	3	1	5.8	2.7
#17	In-situ examination during irradiation	2	0	1	0	1	4	1	1	4	2	6.6	2.9
#20	Radiation effects/damage experience at the host institution	1	0	2	1	3	0	0	1	4	4	6.9	3.1

9



Nuclear Energy



Current or potential productivity of the facility (e.g. fewer high-impact experiments or high-volume sample throughput).

C6

	NE support and activities (performed and a ding the volume of experiments that can be			900	033				á	t	tł	ne fac	ility
	Criteria		100		m	ш				m	-	Mean	Std
#6	Proportion of time to be allocated to direct NE mission work either through GAIN, NSUF, or NE programs.	0	0	0	2	4	3	2	2	2	0	6.3	1,7
#7	Current/past NE support/investment	0	0	2	1	4	2	3	2	0	1	5.9	1.9
#8	Current NE work performed at facility	1	1	0	0	4	1	2	4	1	1	6.3	2.5
#9	User experiment throughput capability	0	1	1	0	1	3	3	3	3	0	6.7	2.1

Combined Criteria



C7



Unique capabilities of the facility including any new technology that has the capability to close technological gaps.

Combined Criteria Unique capabilities of the facility including any new technology.

· Does the capability fill any known gaps in technology?

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#19	Does the facility provide new capabilities?	3	0	1	0	1	1	1	3	2	2	6.1	3.4
#21	Need to define and have new capability be on path toward greater applicability and relevance.	1	0	2	0	2	2	1	4	1	1	6.2	2.6

11



C8



Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite.

Combined Criteria Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.

Fuel materials
Surrogates
Radioactive depU or natU
structural materials
LEU or HEU

Pu and actinides
 Highly-burned fuels

	Criteria	1		2 3	3 4	5	6	7	8	9	10	Mean	Std Dev
#14	Radiation levels allowed for samples	c	1	0	1	1	4	1	3	1	2	6.3	2.5
#18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	1	1	0		0	6	1	3	0	1	5.6	2.4
#24	Is there support of small specimen test technology	4	0) (0	2	1	2	3	1	1	5.5	3.3



C9



Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.

Combined Criteria

Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation.

- · Facility should have a QA program (NQA-1 or equivalent).
- Community standards should be developed and applied.
- · Facility should follow standard procedures for irradiations, sample preparation, etc.

							15	п	В		m			Mean	Std Dev
#23	Applicability of results to development or data goals	4	0	2	0	0	2	0	2	3	1	5.4	3.5		
#25	Standards development including temperature sensing	3	0	1	1	2	1	2	3	1	0	5.2	2.8		



Nuclear Energy

C10



Ability of the facility to produce results that meet the needs of the DOE – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.

Combined Criterion Ability of the facility to produce results that meet the needs of the Department of Energy – Office of Nuclear Energy (including cross-cutting programs) and the nuclear energy industry.

	Criteria	1	2	3	4	5	6	7	8	9	10	Mean	Std Dev
#2	Broad applicability (cross-cutting – i.e. multi-program)	0	0	2	0	1	3	2	2	3	2	7.1	2.3
												7.8	1.8
#5	Nuclear Energy Industry needs	1	1	0	2	2	2	1	4	0	2	6.1	2.7

Appendix C Criteria Weighting Data and Comments

Appendix C

Criteria Weighting Data and Comments

Criteria Weighting – Exercise 1 (pre-workshop exercise)

Votes Cast: 14

No.	Criteria	Avg. Score	+/-	Std Dev	1	2	3	4	5	6	7	8	9	10
1	Scientific merit and potential merit	8.79	26.4%	1.32	0	0	0	0	1	0	0	4	4	5
2	Broad applicability (cross-cutting – i.e., multi program)	7.29	31.7%	2.22	0	0	2	0	1	1	2	3	3	2
3	International capabilities alternatives	4.50	24.9%	1.99	2	0	2	1	6	2	0	0	1	0
4	DOE-NE programmatic mission need	7.93	31.2%	1.87	0	0	0	1	1	1	2	3	2	4
5	Nuclear energy industry needs	6.64	30.2%	2.72	1	1	0	1	2	0	1	5	1	2
6	Proportion of time to be allocated to direct DOE-NE mission work through GAIN, NSUF, or DOE-NE programs	6.36	28.6%	1.72	0	0	0	2	3	3	3	1	1	1
7	Current/past DOE-NE support/investment	5.93	33.5%	2.34	0	0	3	1	4	0	2	2	0	2
8	Current DOE-NE work performed at facility	6.29	29.5%	2.66	1	1	0	0	5	0	1	3	1	2
9	User experiment throughput capability	7.00	27.0%	1.89	0	1	0	0	1	3	3	2	4	0
10	Beam energies (and energy ranges)	7.79	26.0%	1.82	0	0	1	0	1	0	2	5	3	2
11	Ion types and variety	7.79	25.5%	2.04	0	1	0	0	1	0	2	4	4	2
12	Variety of irradiation environments	7.71	28.5%	1.71	0	0	0	1	1	0	4	4	1	3
13	Multiple analytical techniques available	6.21	28.8%	2.60	1	1	0	0	5	0	2	1	3	1
14	Radiation levels allowed for samples	7.14	38.8%	2.33	0	0	0	4	0	2	0	3	2	3
15	Multiple convergent beams (dual or triple)	6.36	27.4%	2.19	1	0	0	1	3	2	2	2	3	0
16	Ability to match prototypic conditions	6.43	29.0%	2.61	2	0	0	0	2	1	4	2	2	1

No.	Criteria	Avg. Score	+/-	Std Dev	1	2	3	4	5	6	7	8	9	10
17	In situ examination during irradiation	7.43	33.5%	3.02	2	0	0	0	1	1	1	1	4	4
18	Supporting infrastructure (hot work facilities, sample preparation, etc.)	6.07	29.2%	2.63	1	0	3	0	0	4	1	3	0	2
19	Does the facility provide new capabilities?	6.93	37.4%	3.37	3	0	0	0	1	0	1	3	2	4
20	Radiation effects/damage experience at the host institution	6.86	33.8%	3.04	1	0	1	1	4	0	0	0	2	5
21	Need to define and have new capability be on path toward greater applicability and relevance	6.93	27.4%	2.46	1	0	1	0	1	2	1	5	1	2
22	Relative R&D impact of utilizing direct simulants (i.e. swift heavy ion) or indirect simulants (i.e., light ions)	5.86	35.6%	2.85	3	0	0	0	2	2	2	2	3	0
23	Applicability of results to development or data goals	5.43	40.9%	3.68	5	0	1	0	0	1	0	2	4	1
24	Is there support of small specimen test technology?	5.21	38.1%	3.43	5	0	0	0	2	1	0	3	2	1
25	Standards development including temperature sensing	5.29	37.3%	2.99	4	0	0	1	1	1	2	4	1	0

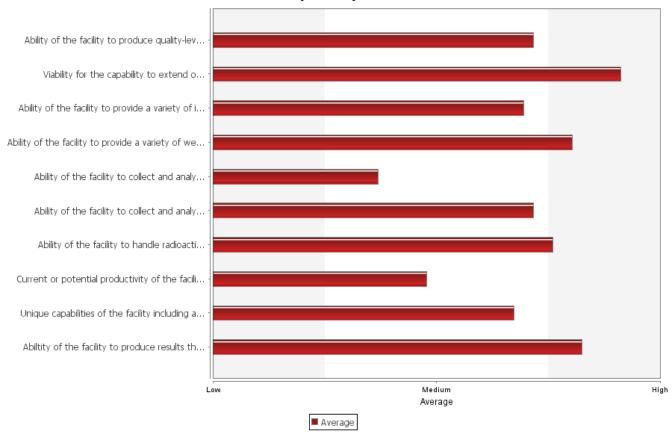
Community Comments on the Criteria (#2)

Criteria	Comments
8. Current DOE-NE work performed at facility	Although it would be preferable that the person in charge of the facility would be very knowledgeable in the issues we need to tackle upfront, a facility with the capability we need and an advisory board composed of knowledgeable persons would allow any facility to satisfy the requirements of the nuclear-energy research community.
12. Variety of irradiation environments	This question is not clear to me. What variety are we talking about? Ion used? Energy? Something else?
16. Ability to match prototypic conditions	This is a tricky question as, for very high dose, such ability has not been demonstrated yet.

Criteria Weighting – Exercise 3 Votes Cast: 23

	Cast. 20	Avg.		Std.			
No.	Low / Med / High	Score	+/-	Dev	Low	Medium	High
1	Viability for the capability to extend our understanding toward accurately simulating nuclear irradiation conditions (neutrons or fission fragments)	2.83	37.9%	0.38	0	4	19
2	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	2.39	28.5%	0.57	1	12	10
3	Ability of the facility to provide a variety of well-controlled target environments and conditions	2.61	28.5%	0.57	1	7	15
4	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data onsite	1.74	33.7%	0.67	9	11	3
5	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in situ	2.43	28.8%	0.58	1	11	11
6	Current or potential productivity of the facility (e.g., fewer high-impact experiments or high-volume sample throughput)	1.96	34.5%	0.69	6	12	5
7	Unique capabilities of the facility, including any new technology that has the capability to close technological gaps	2.35	34.9%	0.70	3	9	11
8	Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite	2.52	50.0%	0.50	0	11	12
9	Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation	2.43	35.6%	0.71	3	7	13
10	Ability of the facility to produce results that meet the needs of DOE-NE (including cross-cutting programs) and the nuclear energy industry	2.65	28.0%	0.56	1	6	16





Community Comments on the Criteria (#3)

Combined Criteria	Comments
1. Viability for the capability our understanding toward a simulating nuclear irradiation conditions (neutrons or fiss.)	"viability for." Someone should improve English here. Also, this one is important but difficult to judge/score since it is too
fragments)	2. While accurately simulating (or informing) the effects of neutron irradiations is the ultimate goal of ion beams, no single capability or facility can achieve this goal. Rather, a collection of complementary capabilities coupled with a robust user community is required. Thus, scoring individual facilities on these criteria seems difficult.
	3. This must be defined by the programs (with input from facilities). We need a collective effort to move forward, and the path forward must be determined before we can decide which facility is best equipped to support such effort.
	4. It is critical to determine the limitations, if any, of the use of ion beam irradiation techniques for the simulation of the impacts of neutron irradiation on materials.
	5. This criterion cannot be quantified, since we don't have a good

Co	mbined Criteria	Co	mments
			idea of what is truly needed to accurately simulate neutron damage in materials from ion beam irradiation. One facility may actually have outstanding potential to produce better results, but AT THIS TIME there is no standard upon which to measure such a claim. Therefore, I graded all facilities the same.
2.	Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.)	1.	The variety of ion beam conditions is one of the most important attributes that will enable a facility to meet the needs of the user community and provide DOE-NE with the data it needs to meet its programmatic mission.
		2.	This speaks to the versatility of the facility, which is an important attribute for an ion beam laboratory, as different conditions may be needed to meet the needs of the experimenter.
3.	Ability of the facility to provide a variety of well-controlled target environments and conditions.	1.	Because of the large number of damage effects and conditions that nuclear materials experience in a reactor, clearly it is important that ion beam facilities be able to provide a method for emulating these conditions.
		2.	This is of importance as the effects of radiation on the behavior of materials in nuclear systems are generally not in isolation. Rather, behavior is due to the combination with high temperature, an aggressive environment, stress, etc.
4	Ability of the facility to collect and	1.	How do we rank a facility according to this criterion?
	analyze materials properties and/or perform microstructural characterization data onsite	2.	Users select the analysis capabilities that are most valuable to their experiments and other than a marginal level of convenience, there is not that much value in the ion beam facility also providing onsite characterization capabilities.
5.	Ability of the facility to collect and analyze materials properties and/or perform microstructural characterization data in situ	1.	The ability to generate dynamic data—i.e., watch or record things as they happen—is not represented with sufficient significance in the general weighting criteria.
6.	Current or potential productivity of the facility (e.g., fewer high-impact experiments or high-volume sample throughput)		
7.	Unique capabilities of the facility, including any new technology that has the capability to close technological gaps		
8.	Ability of the facility to handle radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite	1.	NSUF should provide to the facilities a required format for this information. In order to compare facility to facility, the same description must be used, i.e., total activity, dose rate, and ability to handle special nuclear material.
9.	Ability of the facility to produce quality-level data that can support licensing as well as verification and validation of modeling and simulation	1.	This criterion can be simply restated by determining if the facility has a suitable quality assurance program in place. Ion irradiation data will unlikely be accepted for licensing without the support of mechanism models to correlate ion-neutron damage.

Combined Criteria	Comments
	3. Supporting licensing is definitely important, but it is difficult at this stage since we cannot establish ion-neutron correlation yet.
	4. It is doubtful that ion irradiation alone will lead to licensing. However, only high-quality data will support the efforts toward licensing (which will ultimately be based on neutron data).
	5. It is nearly impossible to quantitatively differentiate the ability of facilities to meet DOE-NE needs. By definition, all invited participants to the workshop were able (on paper) to meet DOE-NE needs. And after reviewing the Excel summary sheet, no one admitted that they were unable or unwilling to perform DOE-NE work. Consequently, I ranked all facilities the same.
	6. Understanding this criterion centers on the word "quality." Researchers view quality as a measure of the precision, accuracy, and impact of their data. Licensing and QA professionals regard "quality" as pertaining to the certification, documentation, and accessibility of the entire data-generation process (i.e., making the data lawyer-friendly). I think the definition of quality for this criterion is the latter. Is that correct?
10. Ability of the facility to produce results that meet the needs of DOE-NE (including cross-cutting programs) and the nuclear energy industry	

Appendix D Ion Beam Users Presentations

Appendix D

Ion Beam Users Presentations

The first day of the workshop was planned for the ion beam user community (researchers and DOE-NE programs) to present their needs to the community. Their presentations are provided here along with any comments made by workshop participants (in the sidebar).

Presentation: NSUF User's Organization

Peng Xu



History and Missions

History and Missions

- Started in 2010
- Defined in UO Charter updated Oct 2013
 - Provide a formal and clear channel for the exchange of information, advice and best practices between the investigators and the NSUF management
 - Serve as an advocacy group for the experimental activities at the NSUF
 - Facilitate communications among NSUF users, partner facilities, and ATR
 - Charter will be updated this year to enhance user engagement

Membership

Membership

- Membership open to anyone interested in the ATR NSUF
 - Users
 - Potential users
 - Past users
 - Scientists and engineers engaged in operation and development of ATR NSUF facilities (including partner facilities)
- · Why you should become a member
 - Receive funding opportunities announcement and research collaboration opportunities in time
 - Run for executive committee
 - Expand your professional network and strength your career
 - Express your concerns and get problems solved

Leadership

Leadership

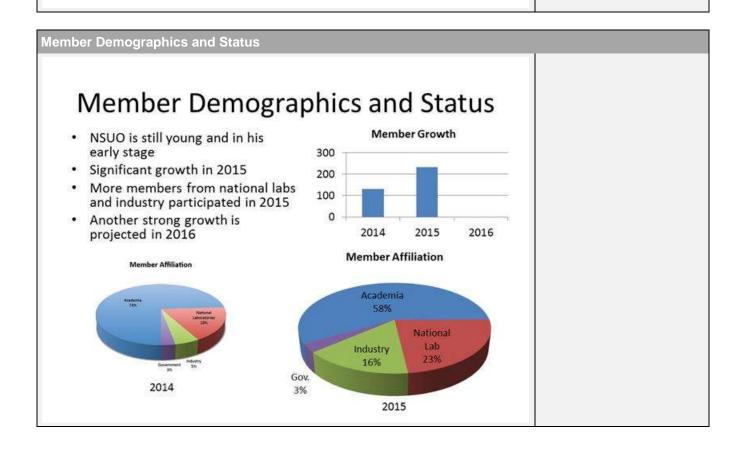
- Executive Committee
 - Seven members, including one student member, nominated and elected by UO membership plus immediate past char as member ex-officio
 - Four-year terms (one-year term for student member)
 - Chair and Secretary/Chair-Elect selected by Executive Committee members
 - Proposed changes in the new charter: adding two more regular members and one more student member
 - Proposed Extension of student membership from oneyear to two-year

Executive Committee Executive Committee Current Members - Chair - Peng Xu, Westinghouse (since - Secretary/Chair-Elect - Yong Yang, University of Florida (since 2013) Parg Xa Wastinghouse Electric Company 123 647 1010 - Ron Ballinger, MIT (since 2014) - Jessika Rojas, VCU (since 2015) Peter Hosemann, UCB (since 2015) - Student Member - Matthew Swenson, **BSU** (since 2015) - Immediate Past Chair - David Senor, eter Wels. Insensity of California, Santa Bertians est/750400mel.com PNNL (since 2012) UO Executive Committee 2016 Spring Election contedience edu 919-315-3667 - Two regular members and one student member

Executive Committee Led Activities

Executive Committee Led Activities

- Provided input/feedback to ATR NSUF management on a variety of topics (mostly driven by comments received from users)
 - Proposal process
 - User engagement
 - Sample library policy
 - Utilization of partner facilities
 - User week meeting
 - Experiment planning, scheduling, and executing
- Created three committees to address specific topics
 - User Week
 - Education and Outreach
 - Capabilities and Infrastructure
 - Membership in committees is open to any UO member and broad participation is encouraged
- Participated in ATR NSUF booth at various national meetings, i.e. ANS Meeting in 2013, TMS meeting in 2014 and 2015



Meetings

Meetings

- · Annual User Week in June at INL
 - The most important event and communication avenue for UO
- Sponsored technical meetings at national conferences
 - 2016 TMS led by Peter and Jim
 - 2016 ANS led by Yong and Keith
- Executive Committee meetings
 - User Week
 - Teleconference as needed, but at least once per quarter
 - National meetings such as TMS and winter ANS
 - Partner facility site meeting is suggested







User Week Committee

User Week Committee

- · Matthew Swenson and Dave Senor, Chair
- Provides input on timing, format, content, location and other aspects of User Week
 - Matthew has been leading the effort and put together a draft of User Week Meeting Agenda for 2016 with comments from the rest of committee members
- User Week is the annual meeting of the UO strong participation and input from members during planning is critical
 - A survey was sent out to all the users to solicit user feedbacks on the user week meeting experience and suggestions on improvement
- · Vision for User Week
 - User Week should be "go-to" meeting for users to share experiences and ideas on ATR NSUF projects
 - · Helps build a vibrant and interactive user base
 - Fosters communication between users and ATR NSUF staff
 - Transitioning from mostly educational format to mostly technical exchange (will retain some educational component to benefit new users)
 - User week meeting has always been hosted at INL
 - · Live conferencing is a great approach to reach out to partner facilities

Education and Outreach Committee

Education and Outreach Committee

- · Jessica Rojas, Chair
- Focuses on growing the UO membership and improving communication with stakeholders
 - Important component to the vision of growing NSUF beyond irradiation testing to embrace the wider nuclear materials and fuels community
 - . Tough goal to achieve since NSUF needs to support NE missions
 - Strong university representation in UO, reflecting early focus of ATR NSUF on university-led research
 - Opportunities now exist to grow industry and national laboratory participation in the ATR NSUF and UO
 - Good accomplishment in 2015
- Current activities
 - Developing NSUO brochure
 - Developing NSUO website



NSUO Website

NSUO Website

https://atrnsuf.inl.gov/default.aspx?Page=Users Organization&id=230

- NSUO website is available from NSUF homepage
- Currently working on information update to be ready for the NSUF website upgrade



Suggestions on Membership and Engagement Improvement

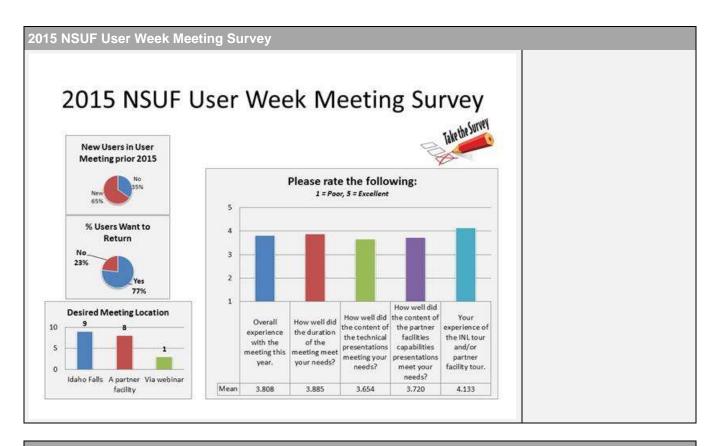
Suggestions on Membership and Engagement Improvement

- · Need member growth
 - PIs of funded experiments automatically become UO members
 - Attendees at User Week or other ATR NSUF workshops automatically become UO members?
 - Ask people to sign up during professional meetings
 - Ask current users to provide referrals
 - Diversification
- · Improve member engagement
 - Suggest to increase rapid turnaround awards
 - Suggest to boost partner facility usage
 - Suggest to sponsor or host technical sessions at professional meetings
 - 2016 TMS Meeting: Accelerated Materials Evaluation for Nuclear Application Utilizing Test Reactors, Ion Beam Facilities and Integrated Modeling — Ion Beam Irradiation and In-situ TEM, organized by James Cole and Peter Hosemann
 - 2016 ANS Meeting: Nuclear Fuels and Structural Materials (NFSM-2016) organized by Yong Yang, and etc.

Capabilities and Infrastructure Committee

Capabilities and Infrastructure Committee

- · Yong Yang, Chair
- Work closely with Brenden Heidrich to support the NEID development
 - Participated in database survey and trial runs
 - Collected and Provided comments to the NEID
 - Participated in NEID Database Review Panel
- Will continue to support future efforts in NEID
 - Ion Beam Workshop



User Feedbacks on Ion Beam Facilities at NSUF

User Feedbacks on Ion Beam Facilities at NSUF

- Academia and national lab users
 - Important education and training function for students
 - Productive and versatile tools for fundamental studies
- · Industry users
 - Tools can be used to expedite product development if used properly
 - Need to show that what we learned from ion irradiation can be used to solve real problems
- Scientific merit

- 1. Interesting point: DOE has a specific role in Nuclear Engineering education that was part of the congressional act that separated the DOE and NRC from the AEC/ERDA history.
- 2. While it is commendable that DOE-NE focuses on program relevant applied research, the university faculty and facilities have education and training as primary tasks.
- 3. But these are not necessarily exclusive objectives. DOE-NE programs can provide good opportunities for training and teaching AND still produce high merit data.

Users Input on Ion Beam Facilities

Users Input on Ion Beam Facilities

		Ranking
Technical Considerations	Beam energies (and energy ranges)	High
	Ion (particle) types and variety	High
	Variety of irradiation environments (vacuum, water, gas mixture, etc.)	Low to Medium
	Multiple analytical techniques available	Low
	Radiation levels allowed for samples	Medium to High
	Types of sample materials allowed (e.g. alpha emitters/ fresh fuels/ irradiated fuels/TRU)	High
	Ability to match prototypic conditions (LWR, advanced reactors, etc.) – High (temperature)	High
	In-situ examination during irradiation (TEM, photon source or other) - Medium	Medium
	Supporting infrastructure (hot work facilities, sample preparation, etc.) - Medium	Medium
	Multiple beam capability	Medium to High
	Damage profile modeling capability - High	Medium to High

Summary

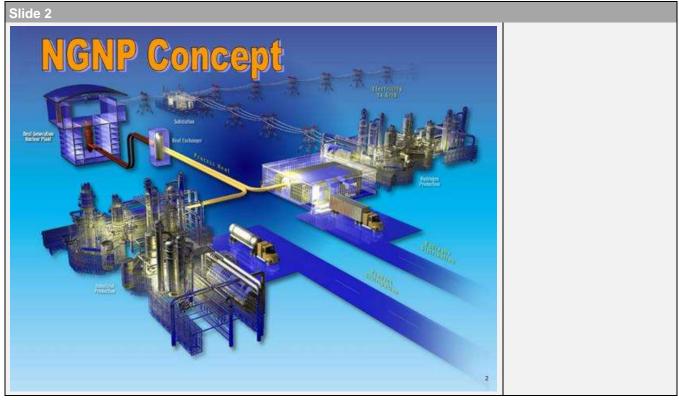
Summary

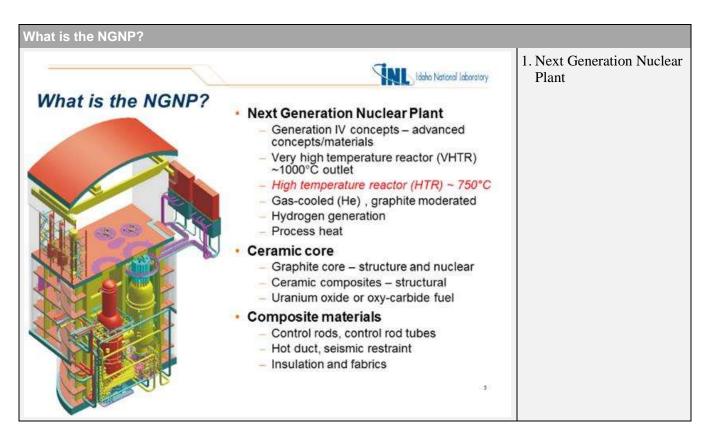
- NSUO is on the right path to become a very vibrant and interactive user group
- · NSUO is a fast growing user group
 - NSUO gained tremendous support from NSUF management
 - Significant improvement on funding
 - Focus of the executive committee
 - There is still significant room to grow the user base and engagement
- If you are not a member of NSUO, I will sign you up!

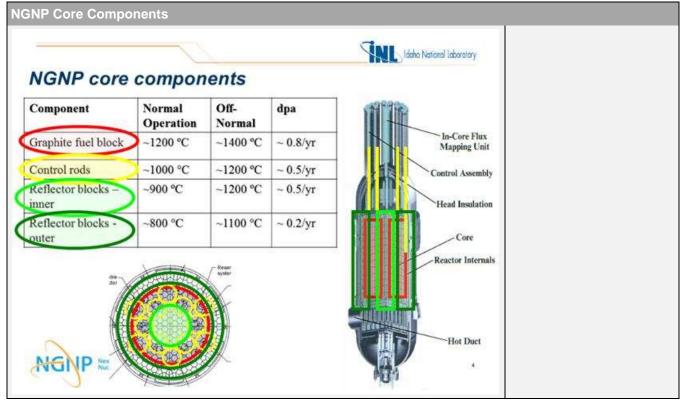
Presentation: Irradiation Material Testing

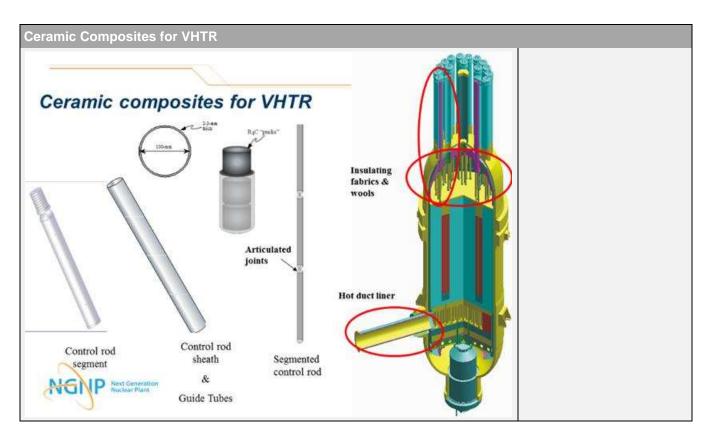
William Windes

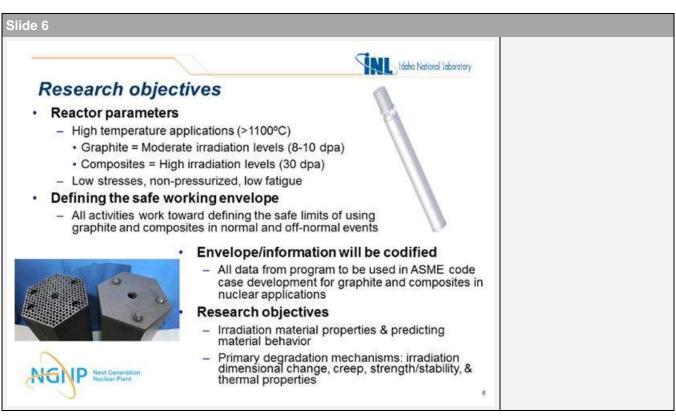


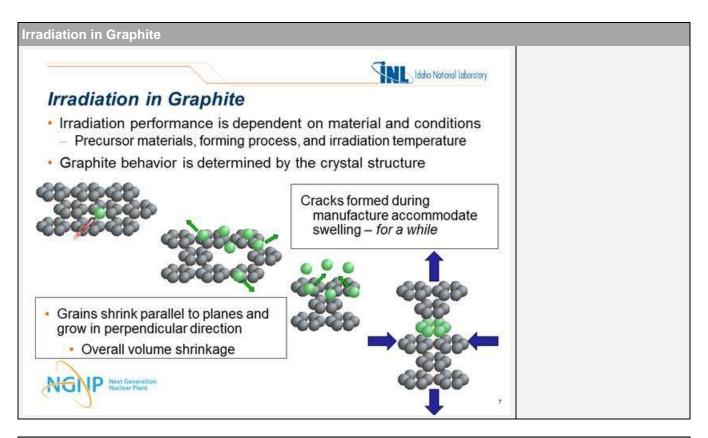


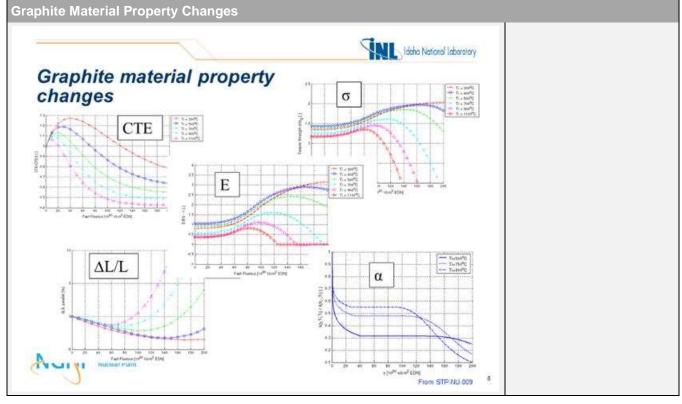


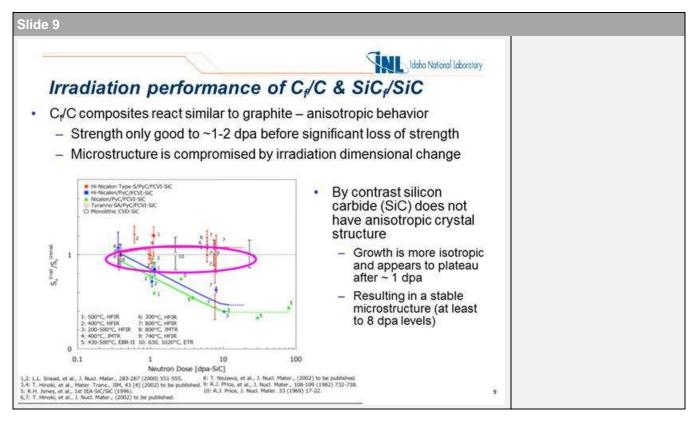


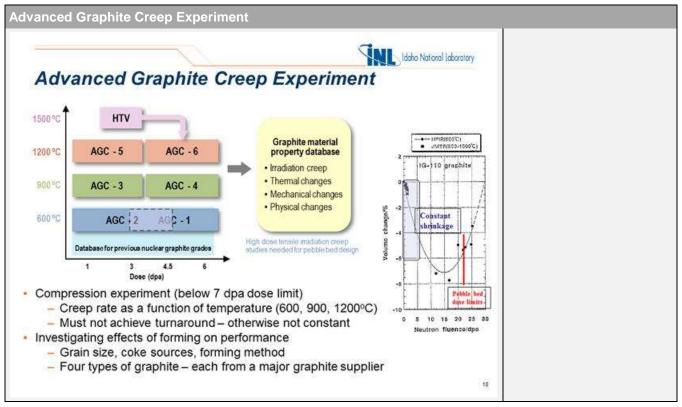












Primary interests in Ion Beam Material Testing



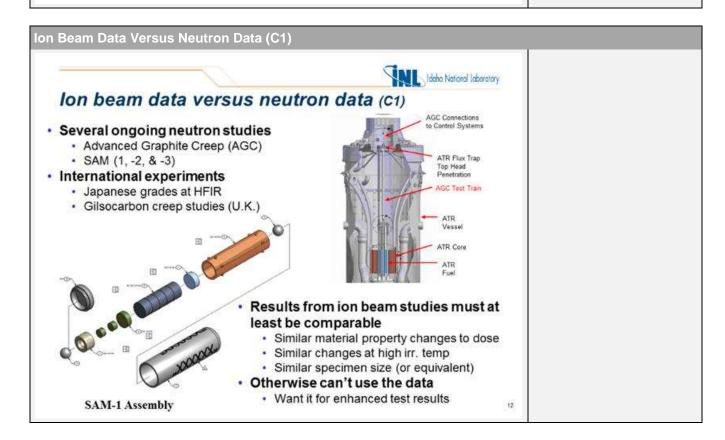
Primary interests in Ion Beam Material Testing

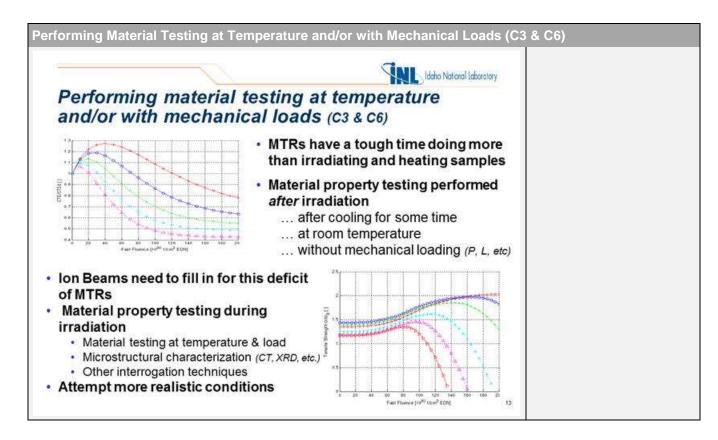
- Provide data/results comparable to neutron irradiation (C1 & C8)
 - Must be comparable to neutron irradiation program (AGC)
 - Must be compatible with previous irradiation programs
- Ability of facility to provide a variety of testing conditions (C3 & C6)
 - Testing over temperature range
 - Testing with mechanical load
- In-situ testing (C4)
 - Underlying irradiation damage mechanisms for material property changes
 - Microstructure characterization and evolution
- NE support (C1 & C5)
 - Require high quality scientific merit data & high volume

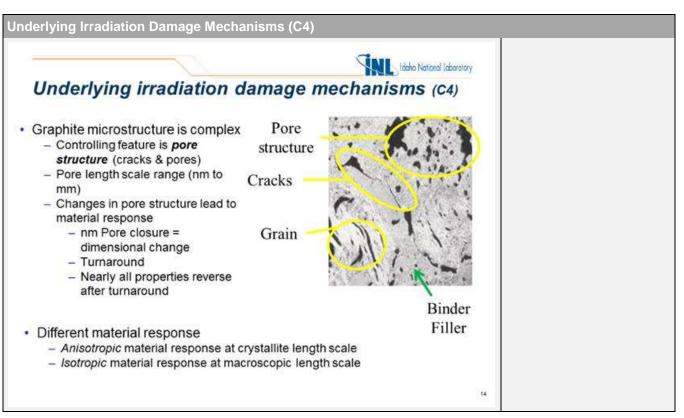
but ...

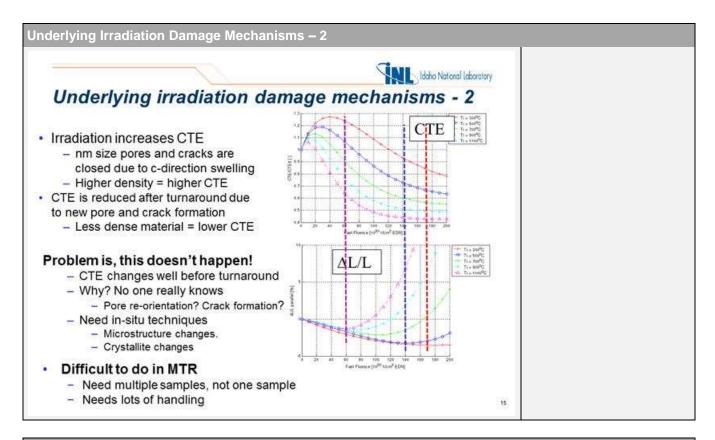
- Quality Assurance (QA) program measures
 - If data is to be codified → Need QA data

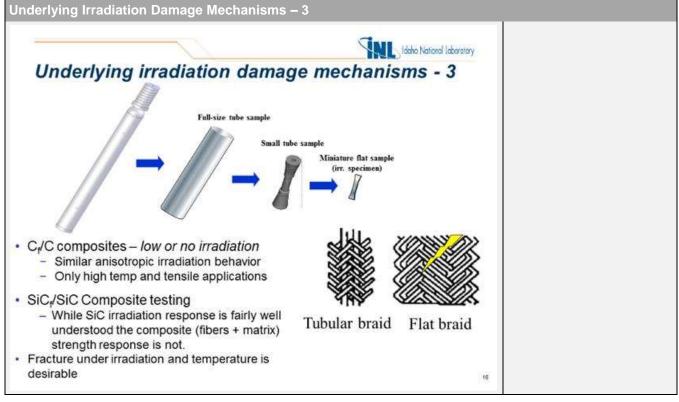
11











High Quality Data for NE Program Support (C5) Idaho National laboratory High quality data for NE program support (C5) All measurements performed to ASTM Standards - Modification of current Standards. - Development of new Standards - New irr. testing guidelines From Dr. Mark Mitchell - PBN Development of ASME Code for Graphite Core Components - Use of a probabilistic design approach Accounts for environmental effects - Requires qualified irradiation data NE programs require QA ASME Code requires qualified data (irradiated & unirradiated) Non-qualified data are scoping studies

- 1. Even without the QA level data (to possibly replace the neutron irradiations), can the ion beam data supplement and possibly reduce the amount of MTR in core testing?
- 2. Show how results were obtained and how they are comparable.

NE Quality Irradiation Data (C5)

material property changes in low activated nuclear materials.

Programs supported

- ART (VHTR Program)
 - AGC, composites, High temp. Metal, AGR fuel matrix, etc.

Glovebox &

benchtop testing

Idaho National Laboratory

- Thermal, physical, mech, chemical (oxid)
- SAM (INL/NSUF Rabbit)
 - SAM-1, -2, & -3
 - Material prep, thermal and physical
- RERTR
- Welding & material prep.
- TREAT
 - Thermal, oxidation, physical

NE quality irradiation data (C5)

- Establish changes between pre and post irradiation material properties.
 - Determining thermal, mechanical, and physical
 - Developed in support of design, construction and licensing data for high temperature gas reactor components.

Experience

- Lab initiated 8+ years ago (2000+ sq.ft.)
- ~ 2700 specimens characterized to NQA-1 standards
- Customized irradiated sample shipping drum
- Materials regularly handled:
 - Nuclear graphite
 - Ceramic & carbon composites
 - Ceramics
- New capabilities
 - Capsule disassembly
 - Specimen prep. (cut saw, TEM disk cutter, etc.)

AGC Specimen Characterization INL's Carbon Characterization Lab (CCL)



AGC Specimen Characterization INL's Carbon Characterization Lab (CCL)

- 2000+ sqft. with 21 analytical measurement stations.
- Complete material characterization
 - Bulk Density
 - Electrical Resistivity
 - Elastic Modulus
 - Strength
 - Coef. of Thermal Exp.
 - Thermal Diffusivity
 - Specific heat
 - DTA/TGA.
- Automated data acquisition and specimen tracking (no clip boards)
- Materials
 - Low level radioactive (<100 mR)
 - Graphite
 - Carbon composites
 - Ceramics
 - Pre-irr. or low dose metals

All measurements performed to ASTM standards.

- STP-Graphite testing for nuclear applications:
 Significance of specimen geometry and population.
- ASME NQA-1 compliant
 - Documented training
 - Periodic system validation
 - National and International traceable calibration
 - Identification and Control of Materials.



Remaining Criteria



Remaining Criteria

Variety of ion irradiations

 While this is important to impose similar irr. damage, more important to achieve similar results from neutron dose

Ability to handle radioactive materials

- Most VHTR core materials are low activation and not much trouble
- However, this is an important consideration for general testing
 - · How are samples shipped?
 - · Shipping container? DOT approved?
 - · Specimen handling and ALARA considerations
 - · In-situ testing and ALARA considerations

Modeling and simulation verification/validation

- VHTR (NGNP) behavior model V&V will come from neutron irradiation
- However, ion beam studies can dramatically assist in data interpretation and model development
 - · Complex experiments that compliment MTR studies would be important
 - Incremental data that "fills in the gaps" between difficult to achieve MTR irradiations will be helpful in developing behavior models.

20

In Summary



In Summary

Data must be comparable to neutron studies - Key criteria

- If we can't compare ion beam studies to neutron results, data is of little use

■ Complex irradiation and novel testing capabilities – Highly desirable

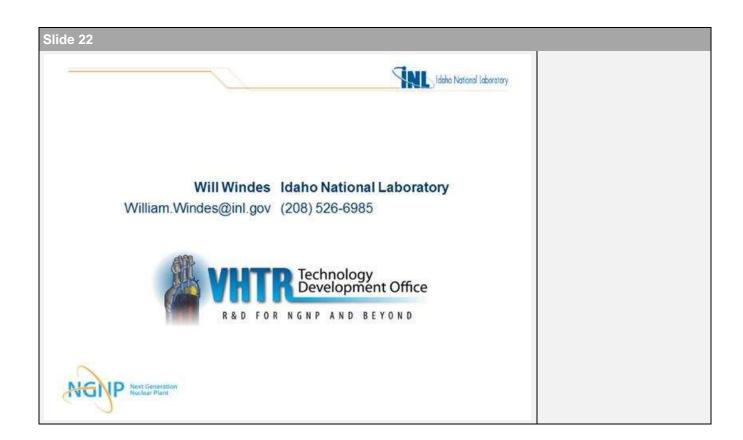
- Complex experiments that compliment the MTR data
- In-situ measurements at temperature and/or load
- In-situ chemical attack (corrosion)
- Internal interrogation (X-ray CT, XRD, others)
- Other unique conditions or interrogation techniques

■ Support NE Material programs (QA program) – Highly desirable

- Need high quality data with scientific merit
- Can support existing data and assist in understanding material behavior (models)
- QA program is necessary (Not just good data, but also a high quality program)
 - · Codified data : Critical criteria
 - · Scoping studies : Highly desirable

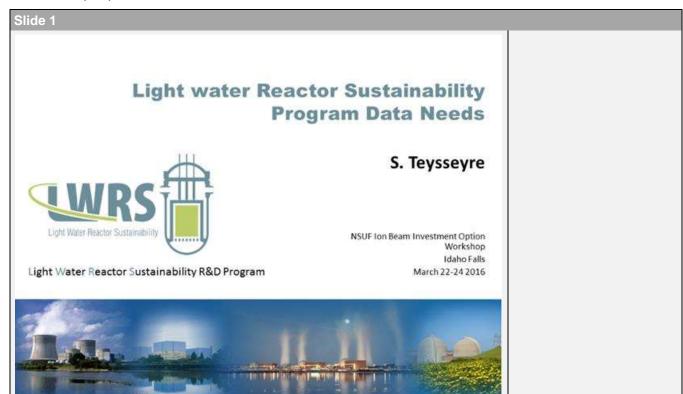
21

- 1. This summary really gets to the heart of what nuclear technology needs. If the ion beam community cannot get to this point, then we will not be able to use this technology in nuclear material irradiation and data use.
- 2. This seems to reflect an interest in having MTR-like conditions that accelerate results to a couple of days. That reflects an immaturity of the models that represent the two modalities. The OA issue is a function of not having a standard controlled setup for each experiment—which is really not an experiment but a parameterization getting the parameters for the model at each point in n space.



Presentation: LWRS Program Data Needs

Sebastien Teysseyre



DOE-NE Light Water Reactor Sustainability Program

DOE-NE Light Water Reactor Sustainability Program

Vision

 Enable existing nuclear power plants to safely provide clean and affordable electricity beyond current license periods (beyond 60 years)

The program is supporting subsequent license extension decisions

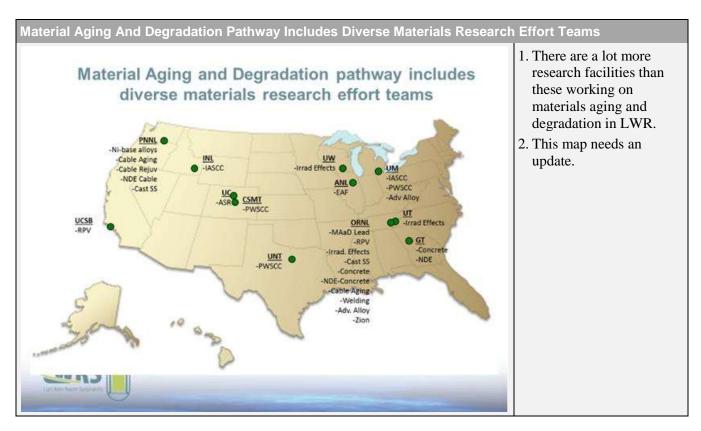
Program Goals

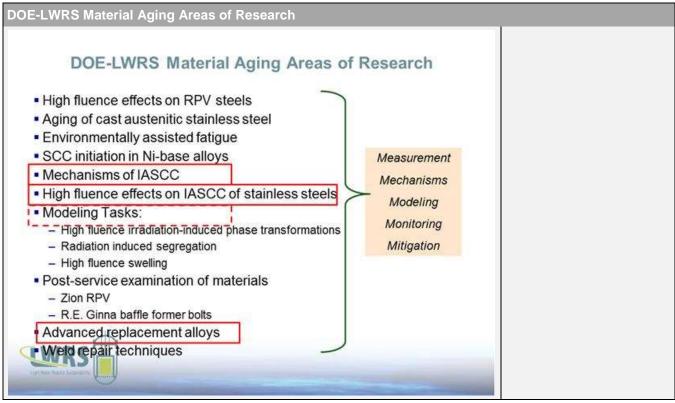
- Develop fundamental scientific basis to understand, predict, and measure changes in materials as they age in reactor environments
- Apply this knowledge to develop methods and technologies that support safe and economical long-term operation of existing plants
- · Research new technologies that enhance plant performance, economics, and safety

Scope

- Materials Aging and Degradation (Metals, concrete, cables, mitigation technology)
- · Advanced Instrumentation and Controls
- · Risk-Informed Safety Margin Characterization
- Reactor Safety Technology







LWRS Program Overview

LWRS program overview

Risk-Informed Safety Margin Characterization. Research and development to develop and deploy approaches to support the management of uncertainty in safety margins quantification to improve decision-making for nuclear power plants. The R&D products will be used to produce state-of-the-art nuclear power plant safety analysis information that yields new insights on actual plant safety margins and permits cost effective management of these margins during periods of extended operation.

Advanced Instrumentation, Information, and Control Systems Technologies.

The R&D products will be used to design and deploy new instrumentation, information, and control technologies and systems in existing nuclear power plants that provide an enhanced understanding of plant operating conditions, available margins, improved response strategies, and capabilities for operational events.

Reactor Safety Technologies. Research and development to improve understanding of beyond design basis events and reduce uncertainty in severe accident progression, phenomenology, and outcomes using existing analytical codes and information gleaned from severe accidents, in particular the Fukushima Daiichi events. This information will be used to aid in developing mitigating strategies and improving severe accident management guidelines for the current light water reactor fleet.



Material Aging Pathway

Material Aging Pathway

- High fluence effects of IASCC of stainless steels
 How will high doses affect the resistance of a component to IASCC?
 - · Main issue: lack of materials.
 - · How can we generate the materials needed for the study?
 - · Is it relevant to "re-irradiate" a material?
 - · Can we use an alternative to neutron irradiation?
 - · Do we have the tools to focus an irradiation campaign?
- Advanced Replacement Materials (collaboration with EPRI's Advanced Radiation Resistant Materials program)
 - · Development of materials with improved radiation resistance
 - · Increase knowledge on less used alloys in nuclear environment



1. If the damage caused by ions and neutrons is different, will re-irradiated materials tell us anything?

Irradiation Needs

Irradiation Needs

- Generation of highly irradiated materials (>50 dpa)
 - · If ion beam is to be used, validation of ions for high fluence is needed
 - · Flux rate effect is a major concern that must be addressed
 - Understanding the developing microstructure which will lead to developing modeling/simulation codes that will allow researchers to utilize less costly alternatives to neutron irradiation experiment campaigns and/or better plan irradiation campaigns.
- Down selection of radiation damage tolerance for the Advanced Replacement Materials.

Needs:

- · Variety of beam (protons, Fe, Ni)
- · Ability to offer multiple beams
- Ability to control irradiation condition (temperature control, energy)
- · Ability to handle radioactive material would be a plus

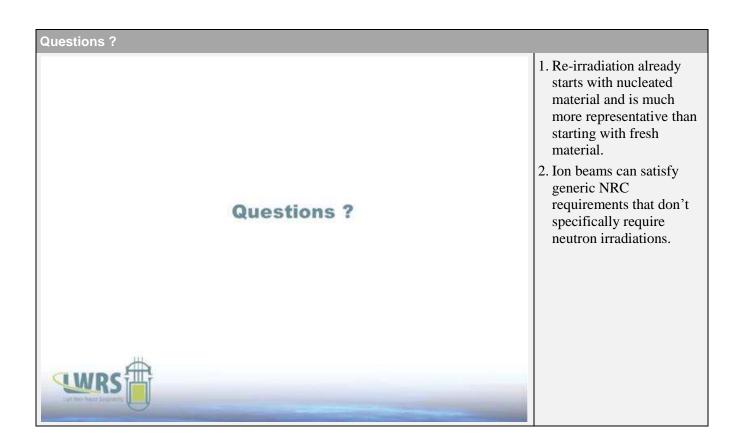


Ion Beam for Characterization

Ion beam for characterization

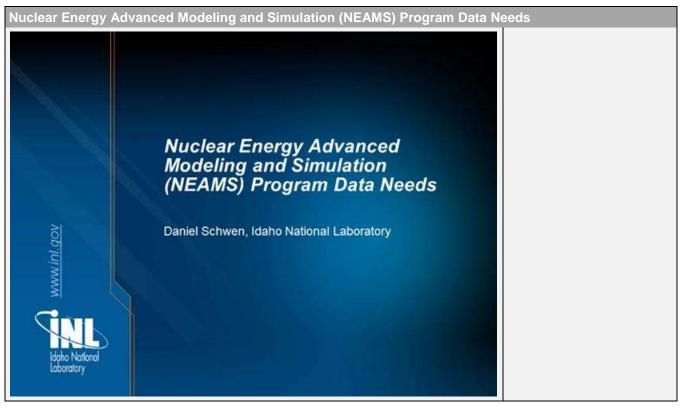
- Characterization of cracking (3D tomography, local strain, local changes in material composition ...) could support the LWRS mission to understand IASCC initiation and propagation.
- Limited usage of in situ characterization (IVEM) under LWRS. However, fundamental work on irradiation damage, potentially using such equipment, would benefit LWRS
- 1. This is a whole different application of ion beams than we have been discussing—may fall better into a PIE category of the eight criteria.
- 2. On the characterization of cracking: what would an ion beam facility bring to the table here?

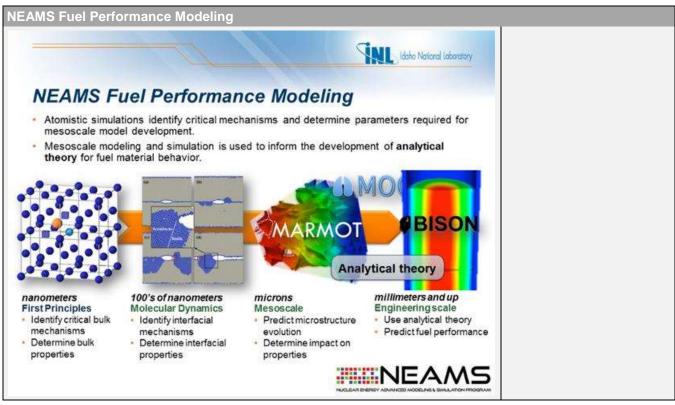


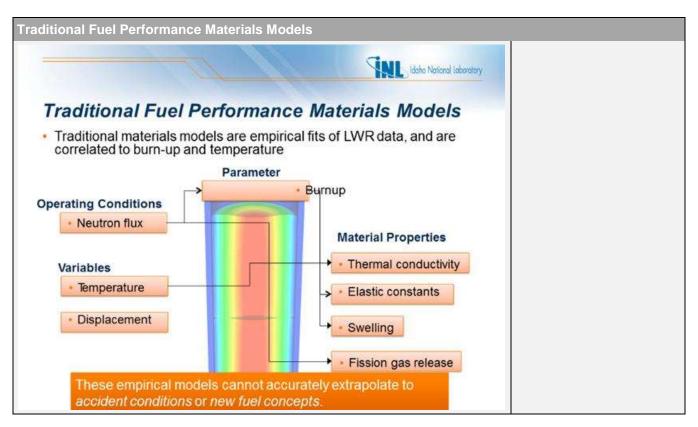


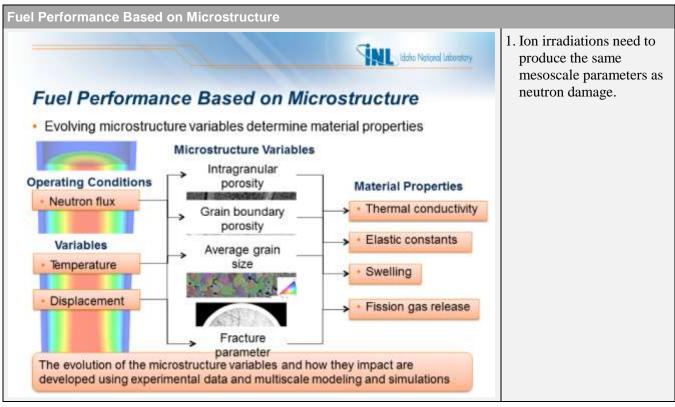
Presentation: Nuclear Energy Advanced Modeling

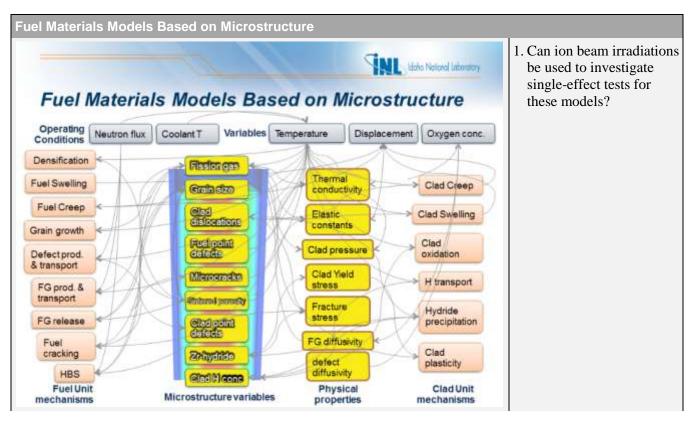
Daniel Schwen

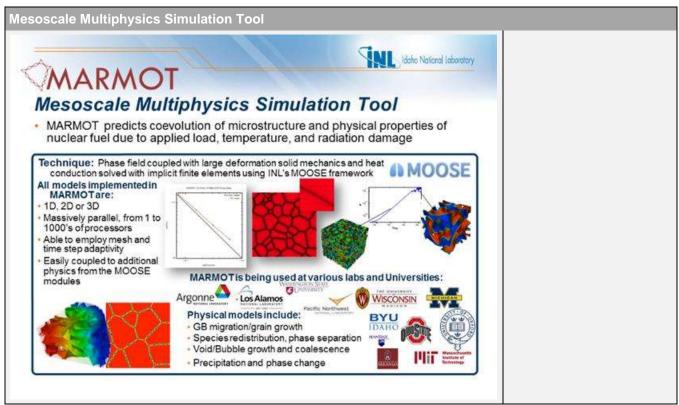


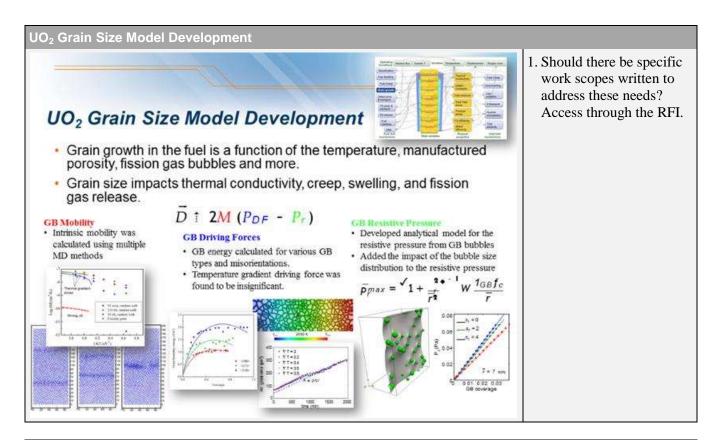


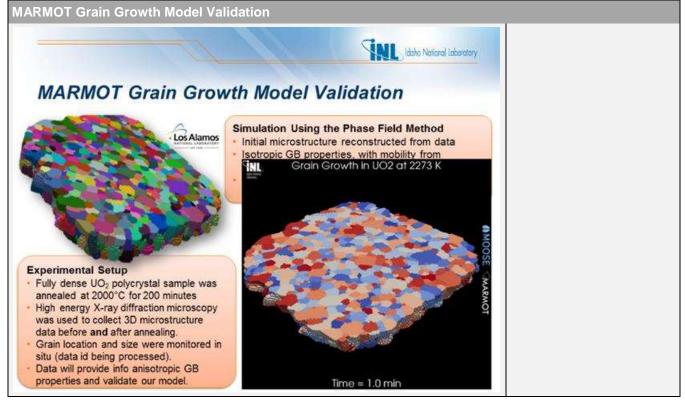




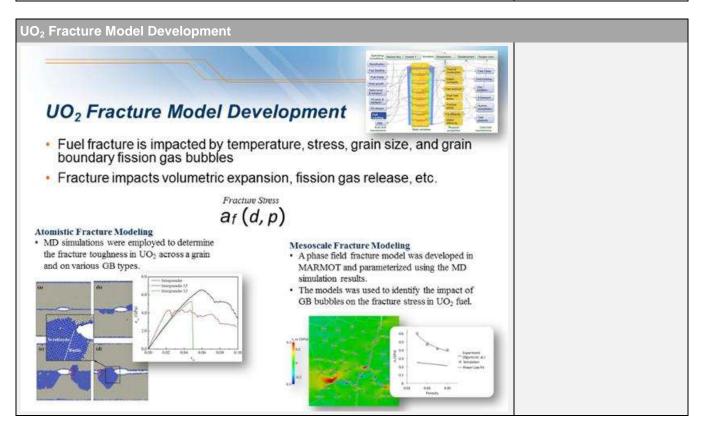


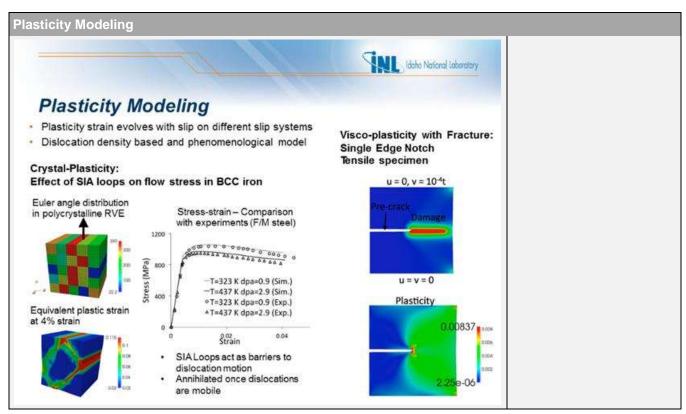


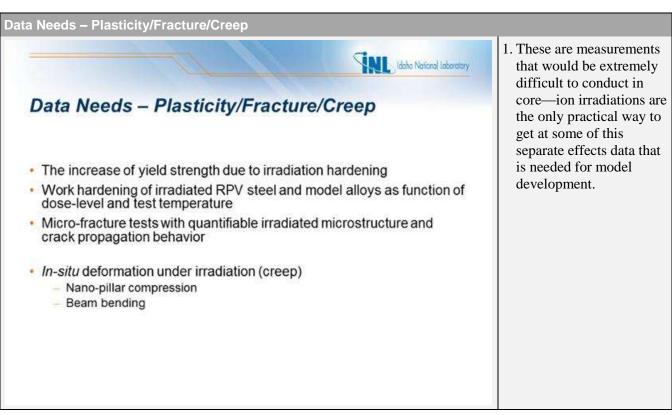


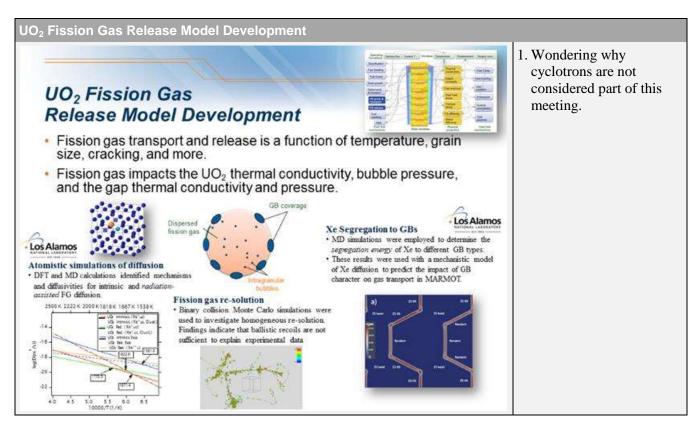


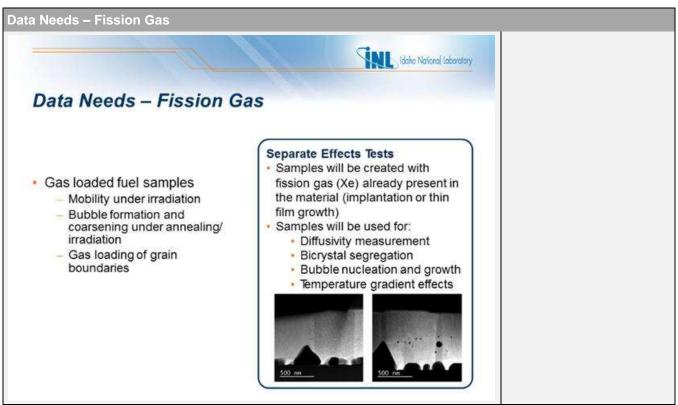
Data Needs – Grain Boundaries • Grain boundary mobility under irradiation (in situ) - Well characterized nanoscale samples (FIB) Bicrystal Data • Experimental techniques have been developed to measure specific mobilities. • These approaches have never been applied to UO₂.

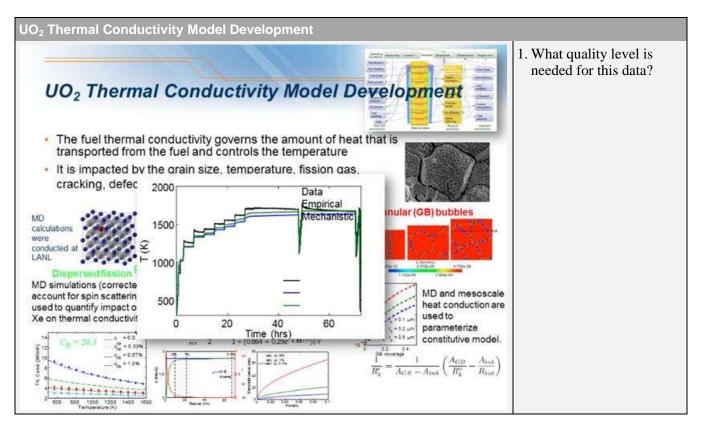


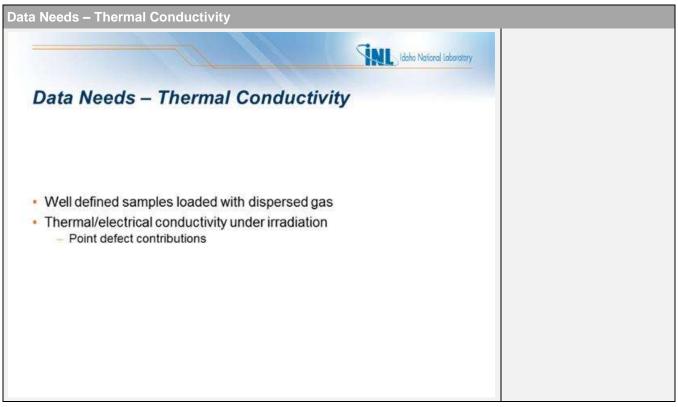


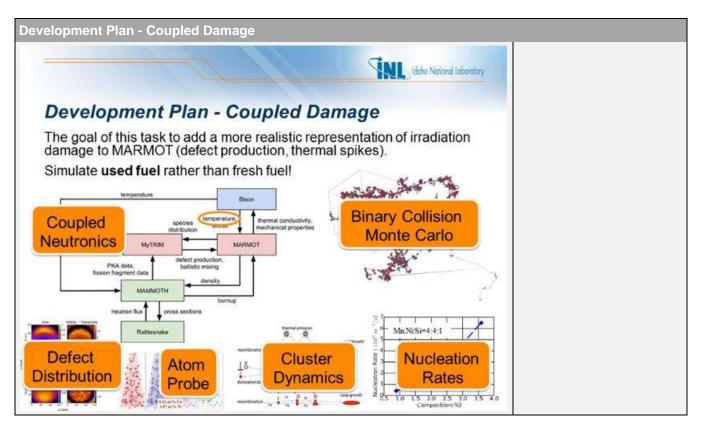


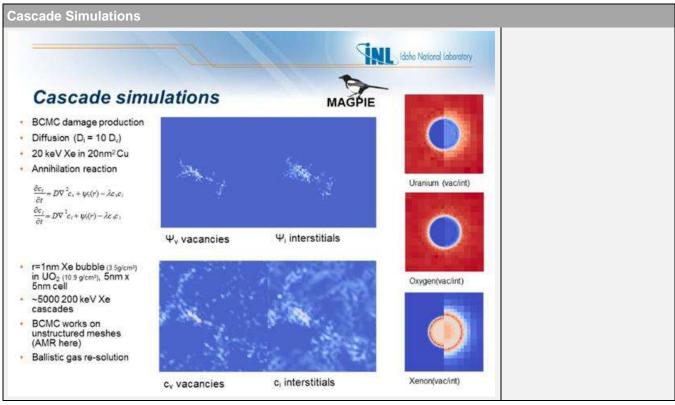






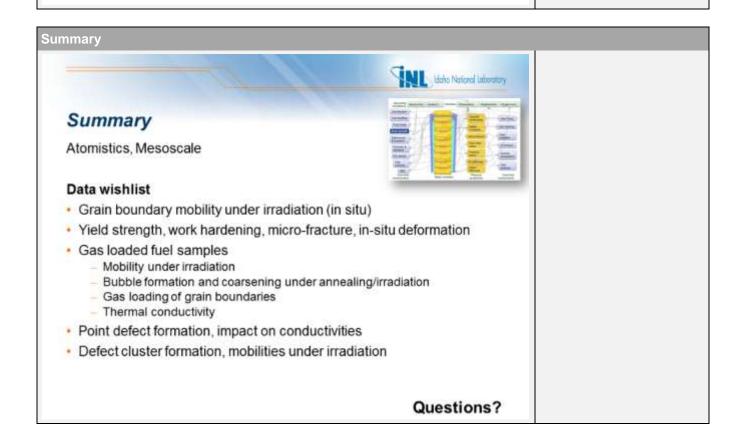






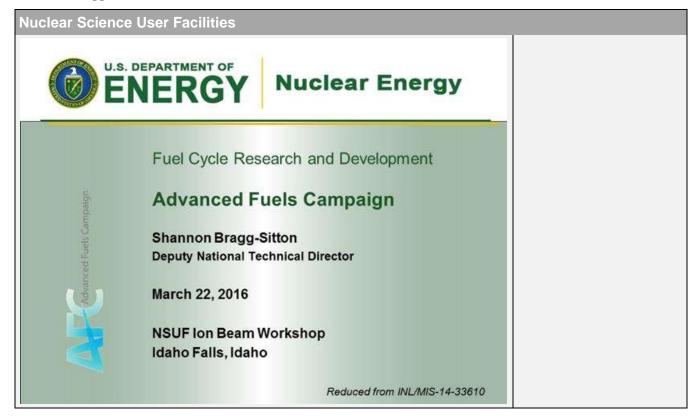
Data Needs – Damage Production • Cluster dynamics input - Mobilities under irradiation (defect clusters, impurities) - Cluster size evolution / growth rates • TRIM/SRIM validation

Thermal/electrical conductivity under irradiation

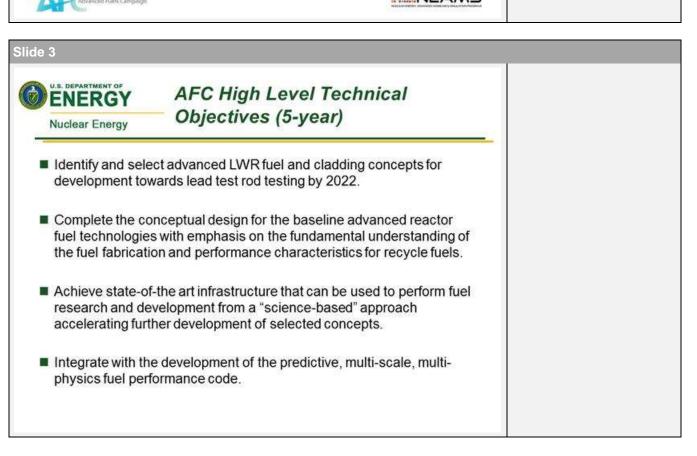


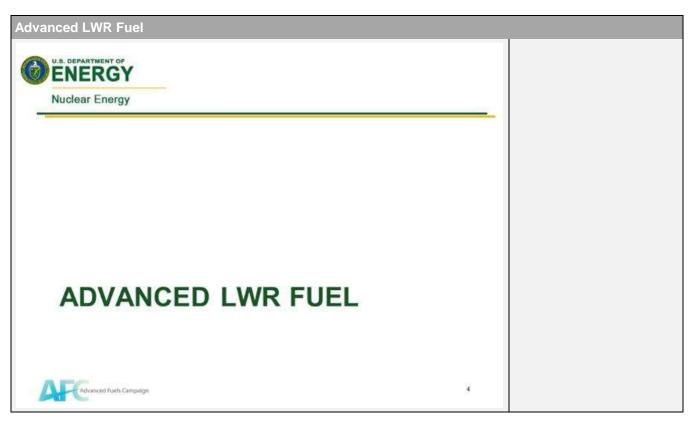
Presentation: Fuel Cycle R&D

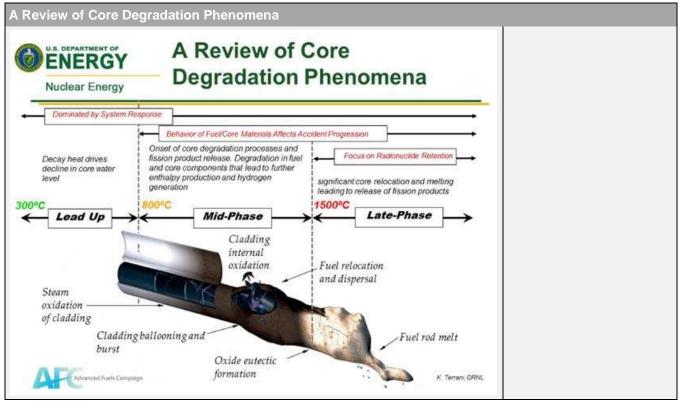
Shannon Bragg-Sitton

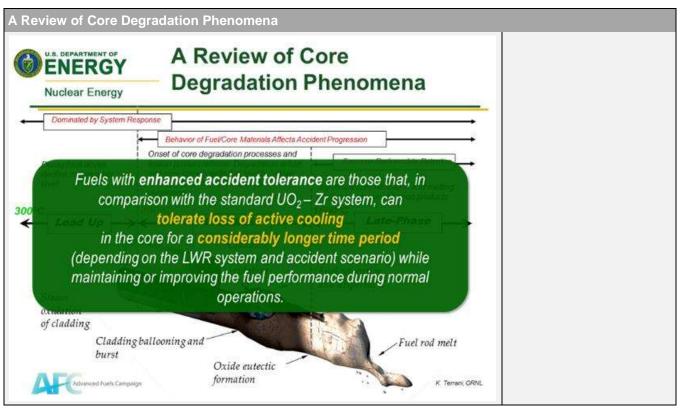


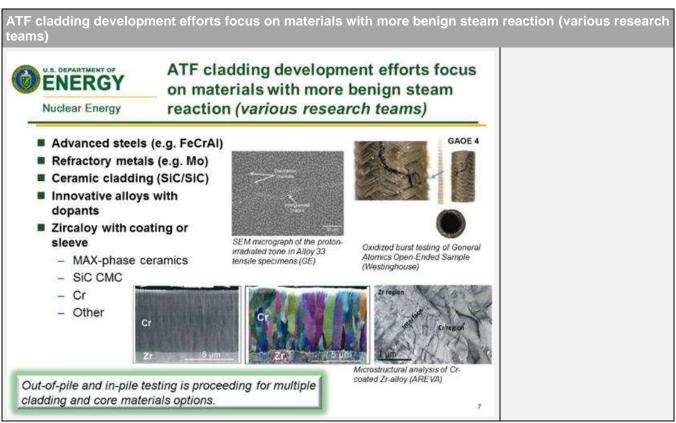
The FCRD Advanced Fuel Campaign is tasked with development of near term accident tolerant LWR fuel technology and performing research and development of long term advanced reactor fuel options. 1. Fuels will experience The FCRD Advanced Fuel Campaign is tasked with U.S. DEPARTMENT OF thousands of dpa as they development of near term accident tolerant LWR fuel ENERGY reach high burnup. I technology and performing research and development of **Nuclear Energy** wonder if ion beam long term advanced reactor fuel options. irradiation is especially useful for some features. Fission spike damage Advanced LWR Fuels with enhanced performance, safety, and reduced waste Advanced reactor fuels with enhanced proliferation resistance and would be dominant. It's not the case where ions are comparable to multi-physics iel performanc modeling and simulation neutrons. 2. Some basic property Capability Development for Science-based Approach behavior can be explored, to Fuel Development though. - Advanced characterization and PIE techniques - Advanced in-pile instrumentation - Separate effects testing - Transient testing infrastructure **MENEAMS** Advanced Foets Campaign

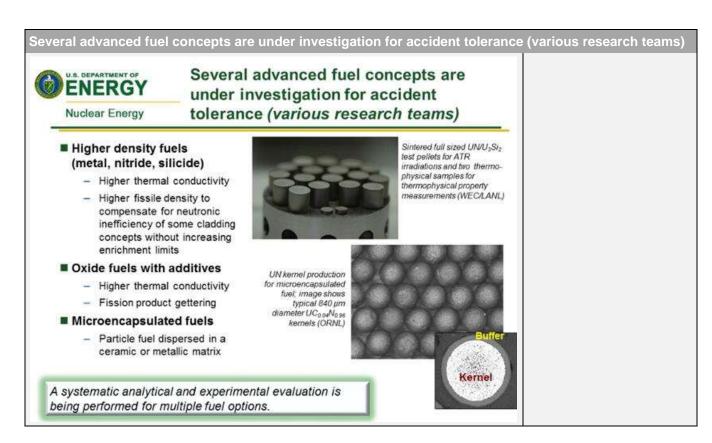


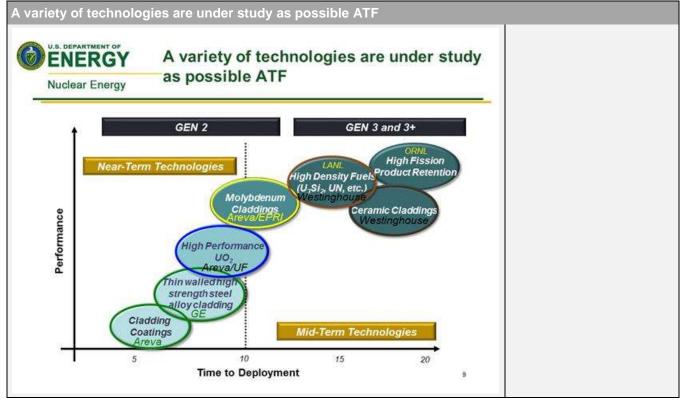


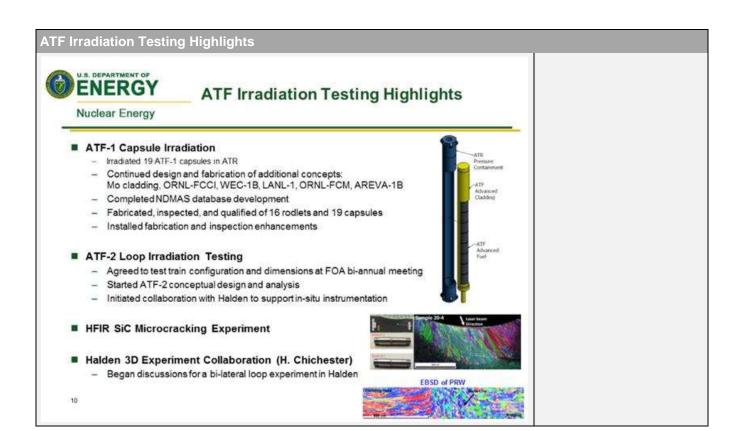


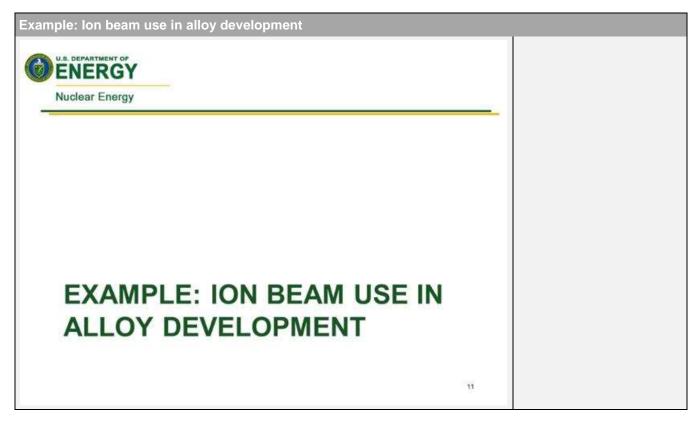


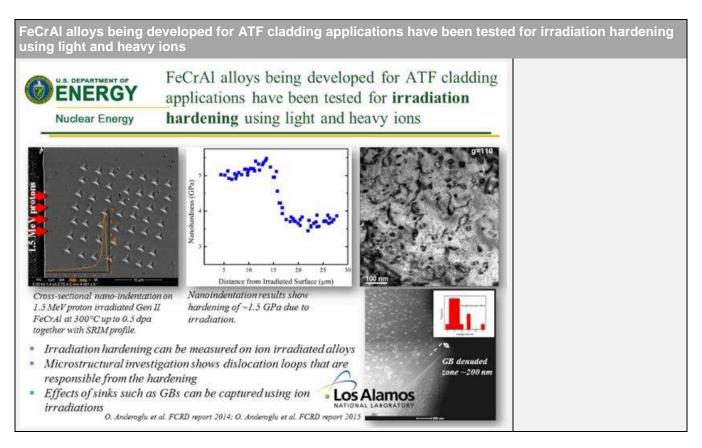


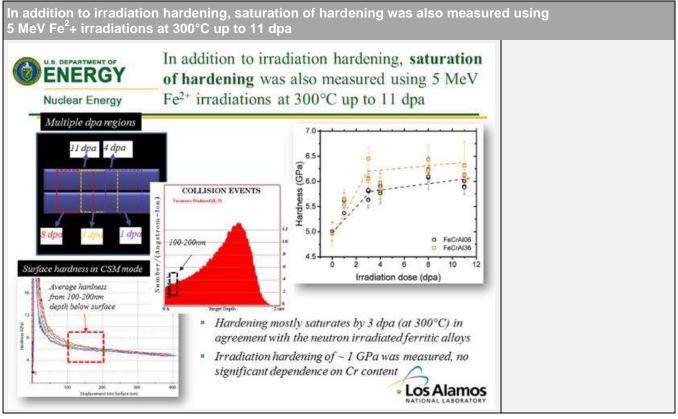










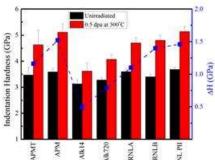


Ion irradiations very effective in surveying a large number of candidate alloys



Nuclear Energy

Ion irradiations very effective in surveying a large number of candidate alloys



Alloy	C	Si	Mn	Cr	Al	Mo	Fe	Y2O3	Ti	Y
APMT	.08	.7	4	20-24	5	3	Bal	2	55	
APM	.08	.7	.4	20-24	5.8		Bal	7.6		
Allcrothal 14	.08	.7	.5	14-16	4.3		Bal	2.0	38	
Allcrothal 720	.08	-7	,7	12-14	4		Bal	85	235	
MA956	.04			20	4.5		Bal	.5	.4	
PM2000	.01	-	-	20	5.5	-	Bal	.5	.5	
ORNL A	.004	-5	-	14.98	5.02		79.87		-	.033
ORNL B	.005		33	17.51	2.93		79.54		98	.017

- A large number of candidate alloys were tested at the same time
- No dependence on the Cr was detected
- Rate sensitive defects (e.g. α') were not found



1. No particular QA was needed for the ion irradiations—ions were used as a first cut to focus the research on the highest performing samples.

Benefits of Ion Beam Irradiation in Cladding Development



Nuclear Energy

Benefits of Ion Beam Irradiation in Cladding Development

Rapid development of datasets for multiple materials and dose levels

- Rapid irradiation to desired dpa
- Can design test to achieve multiple dpa levels in a single sample
- No surface activation
- Rapidly move from irradiation to microstructural characterization
- Provide data for code development prediction of microstructural changes as a function of ion irradiation

Available measurements that match well to neutron damage

- Mechanical Properties: Hardness, evolution of hardness with increasing dpa
- More challenging, but possible: yield stress, work hardening rate
- Post-irradiation microstructural testing
- Some testing of simultaneous irradiation and corrosion (LANL, UM)



Challenges / Needs for Ion Beam Irradiation in Cladding Development



Nuclear Energy

Challenges / Needs for Ion Beam Irradiation in Cladding Development

1. Is this dedicated proton option available in any current facilities?

Challenges / Needs

- High irradiation rate results in more defects in a small area:
 Ability to replicate neutron damage with protons decreases for properties that depend on the time required for damage to precipitate out
- Knowledge of the impact of the defect flux on processes is important
- Ion irradiation physical sample size limits the ability to conduct post-irradiation mechanical testing
- Measurement of processes in situ would be very beneficial:
 - Creep
 - · Fatigue
 - · Other mechanical properties

Possible option:

Dedicated proton facility allowing automated sample irradiation over weeks to months vs. hours to a day in duration

- Allows for larger sample size for subsequent characterization tests
- Addressed defect precipitation issue



16

Slide 17



Nuclear Energy

Thank You



Presentation: Used Fuel Disposition

Remi Dingreville



Outline

Outline

Used Fuel Disposition (UFD) campaign overview:

- Mission and objectives: Storage / Transportation / Disposal
- UFD R&D in the context of ion beam irradiation capabilities

Storage and transportation:

- Cladding: High-burnup cladding performance
- Cladding: Pellet/clad delamination
- Cladding: Radiation annealing
- · Bolted cask: Embrittlement of elastomer seals

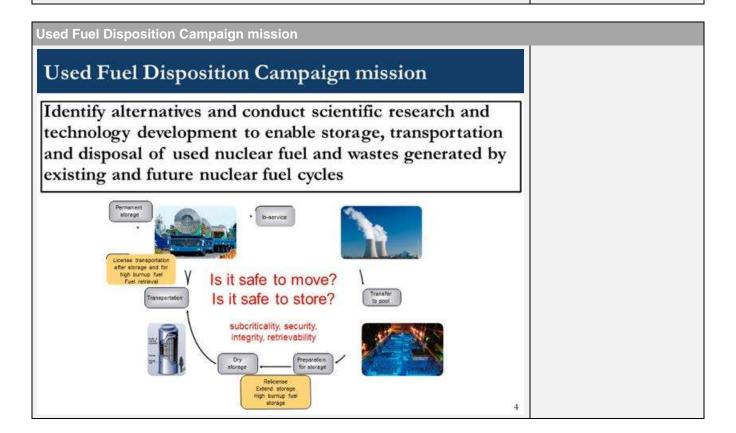
Review of criteria

Historical and projected spent nuclear fuel (SNF) Historical and projected spent nuclear fuel (SNF) 1. Zircaloy 4 is the cladding used on most of the and high-level radioactive waste (HLW) in the U.S. currently stored fuel. 2. CEA and AREVA have Historical and projected Projected volumes done significant ion commercial SNF discharges of SNF/HLW in irradiation of zirc alloys. 2048 HLW Historical and Projected Commercial Used Nuclear Fuel Discharges 7165 99 Operaing Reactors at 61 Sites **DOE** 3% 25,555 19 Shutdown Reactors at 16 Sites SNF 70.000 49,000 50,000 60,000 183,896 85% 1860 Commercial SNF

Volumes in m¹ (assuming constant rate of nuclear power generation and packaging of future commercial SNF).

3

Currently over 1500 casks loaded in the US located at 50+ interim storage



Used Fuel Disposition Campaign mission

Used Fuel Disposition Campaign mission

Identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles

Storage and transportation R&D focus:

- · Extended storage of UNF
- · Fuel retrievability and transportation after extended storage
- Transportation of high-burnup UNF (>45 GWd/MTU)

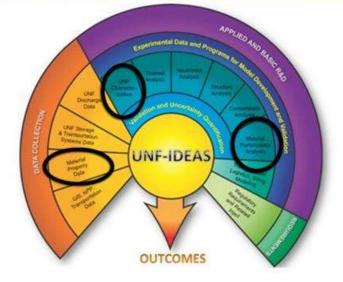
Disposal R&D focus:

- · Sound technical basis for multiple viable disposal option in the US.
- Increase confidence in robustness of generic disposal concepts
- Develop the science and engineering tools needed to support disposal concept implementation

4

Slide 6

UFD R&D data needs in the context of ion beam irradiation capabilities



[Courtesy of] Scaghone, ORNL]

.

UFD data need drivers

UFD data need drivers

What data already exists and relevance to UFD mission

- · Data collected within UFD campaign.
- Proprietary data (e.g. ZIRLO™, M5®).
- · How do we interpolate gaps between existing data points?

Relevance of data w.r.t. regulatory performance criteria for storage and transportation?

- · Metrics extracted from 10CFR71, 10CFR72.
 - "...spent fuel cladding must be protected during storage against degradation that leads to gross ruptures..."
 - "...degradation of the fuel during storage will not pose operational safety problems w.r.t. its removal from storage."
- · Recommendations from SFST-ISG-11.3 and NUREG-1567.

Where are the data gaps and why?

- Access to high burn-up data difficult to obtain? What about newer alloys?
- Compliance: DOE Order 435.1 "Radioactive Waste Management".
- · Separate effects testing.
- NRC and industry data needs?
- · When do we stop collecting data relevant to UFD needs?

- 1. When are the data good enough to deploy?
- 2. Since NRC doesn't provide guidance for research needs, how do you know what is necessary for storage? Is this DOE's thought? What does NRC think?
- 3. DOT data needs are probably different from NRC and DOE.

Gaps for storage and transportation

Gaps for storage and transportation

Degradation mechanisms	Storage importance
Annealing of radiation damage	Н
H ₂ effects: embrittlement and reorientation	Н
H ₂ effects: delayed hydride cracking	Н
Oxidation	М
Creep	M
Corrosion and SCC	M
Thermal aging effects	M
Corrosion: blistering	M
Corrosion atmospheric	Н
Corrosion: aqueous (pitting, crevice)	Н
Thermo-mechanical fatigue of seals and bolts	M
Freeze-thaw	М
Corrosion of embedded steel	M

[Gap Analysis to Support Extended Storage of UNE FCRD 2011]

Ion beam irradiation capabilities that could help

Ion beam irradiation capabilities that could help closing data gaps

- Do we have sufficient data on cladding and fuel assembly materials once they are stored (e.g. high-burnup)?
- · Probability of degradation mechanism occurring?
- · Regulatory considerations?
- Impact on safety functions (Retrievability, Radiological Protection, Thermal Performance, Confinement, Subcriticality)?

Storage and transportation R&D:

- · Extended storage of UNF
 - Cladding: Annealing of radiation damage.
 - Bolted cask: Embrittlement of elastomer seals.
- · Fuel retrievability and transportation after extended storage
 - Cladding: High-burnup cladding performance.
 - Cladding: Hydride reorientation and embrittlement.
- · Transportation of high-burnup UNF
 - Cladding: Pellet/clad delamination.
 - Fuel: Pellet/pellet bonding.

1. Would the facility need to accept highly burned fuel?

1

Ion beam irradiation capabilities that could help

Ion beam irradiation capabilities that could help closing data gaps

- Emulate Initial storage materials conditions (materials damage).
- Emulate alpha irradiation during storage.
- Handle irradiated materials.
- Have the ability to perform accelerated aging.
- Collect microstructural characterization in coupled environments.

Storage and transportation R&D:

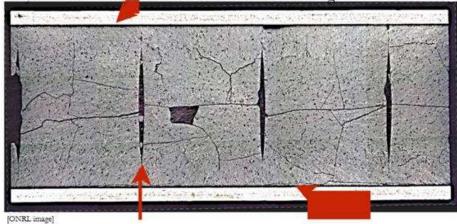
- · Extended storage of UNF
 - Cladding: Annealing of radiation damage.
 - Bolted cask: Embrittlement of elastomer seals.
- · Fuel retrievability and transportation after extended storage
 - Cladding: High-burnup cladding performance.
 - Cladding: Hydride reorientation and embrittlement.
- · Transportation of high-burnup UNF
 - Cladding: Pellet/clad delamination.
 - Fuel: Pellet/pellet bonding,

á

Most of the data needs are related to the performance of high burn-up fuel pins

Most of the data needs are related to the performance of high burn-up fuel pins

Hydride formation/re-orientation in the cladding.



Pellet/pellet bonding

Pellet/clad debonding

- Integrity of spent-fuel (retrievability and transportation) is highly dependent on cladding and fuel pin performance.
- Lack of data for actual high burn-up fuel due to operational

9

Hydride reorientation and embrittlement (M/H)

Hydride reorientation and embrittlement (M/H)

Influencing parameters

§ Temperature, H concentration, crystallography, defect density, stress level, solubility limit.

· Data already available

§ Terminal Solid Solubility (TSS), optical microscopy quantification of precipitation morphology (Arborelius, Motta, Billone, Chung), in-situ XRD

Data needs:

- § Radial-hydride formation below licensing limits (400°C) on irradiated cladding materials.
- § Effect of peak cladding temperature and pressure on hydride formation mechanisms in irradiated materials: Ductile-to-Brittle Transition Temperature (DBTT).
- § Collect microstructural information on interaction between hydride and deformation mechanisms of (irradiated) cladding matrix.
- § Data on fracture toughness for various burn-up level is scarce at best.
 - § No data on radial hydrides cladding.

§ Data on ZIRLO™, M5®.

Pellet/clad delamination (M/H)

Pellet/clad delamination (M/H)

Influencing parameters

§ Temperature, loading mode, burn-up, composition, interface roughness, interface chemistry (intermixing).

· Data already available

§ Data associated with in-reactor behavior (fission product swelling, reactivity induced accident).

· Data needs:

- 6 Characterization of interfacial features (roughness, void structure, etc.) and environmental factors (thermal/irradiation) on delamination process.
- § Interfacial fracture toughness data for pellet/clad interfaces (not to mention high burn-up) does not exist to date.
- § Interfacial fracture toughness data for pellet/pellet interface. Emulation of irradiated fuel?

11

Radiation annealing (M)

Radiation annealing (M)

Influencing parameters

§ Temperature, loading mode, burn-up, composition.

Data already available

§ Hardness tests vs. annealing temperature (Ito, 2004).

Data needs:

- § Low-temperature annealing studies applicable to extended storage (over long period of time).
- § Hardness recovery of irradiated cladding materials (especially for newer alloys ZIRLO™, M5® [high burn-up]) as a function of time during long term annealing.

Embrittlement of elastomer seals/polymeric neutron shields (L)

Embrittlement of elastomer seals/polymeric neutron shields (L)

- · Influencing parameters
 - § Temperature, composition, alpha irradiation.
- · Data already available
 - § Rubber-glass transition temperature for unirradiated samples (BAM, Germany).
- Data needs:
 - § Study of coupled alpha irradiation and temperature on cross-linking of polymer?
 - § Failure of elastomer seals.

13

Review of criteria

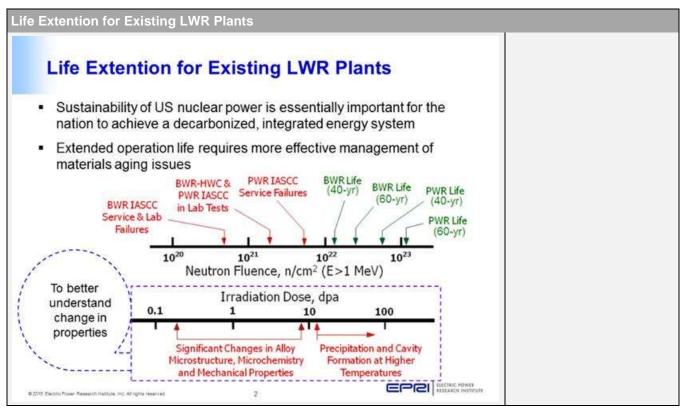
Review of criteria

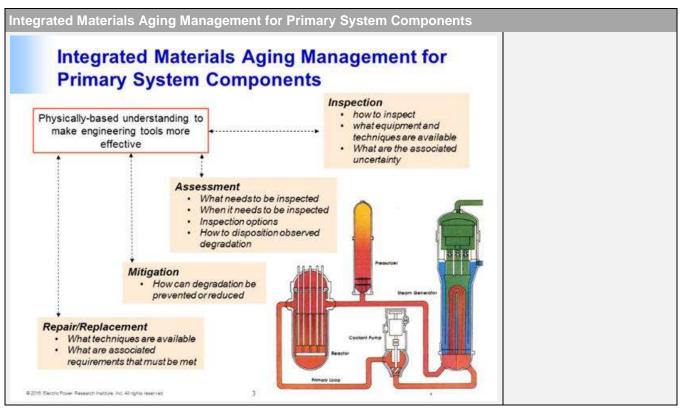
Criterion	Priority
Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry.	HIGH*
Ability of the facility to provide a variety of ion irradiations (ion types, energies, multiple beams, etc.).	MEDIUM
Ability of the facility to provide a variety of irradiation environments and conditions.	MEDIUM
Ability of the facility to collect microstructural characterization data onsite and in-situ.	HIGH
NE support and activities (performed and anticipated) at the facility including the volume of experiments that can be handled.	LOW
Unique capabilities of the facility including new technology.	
Ability of the facility to handle radioactive materials in the beams and elsewhere onsite.	
Ability of the facility to produce high quality data that can support verification and validation for modeling and simulation.	HIGH

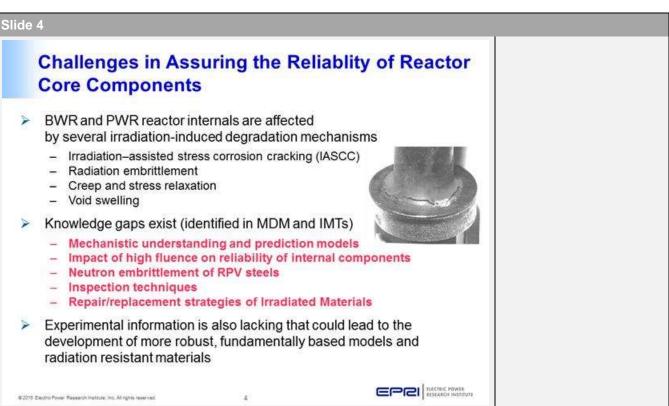
Presentation: EPRI

TG Lian









Challenges in Industry Irradiated Materials Studies Nearly all materials are susceptible Extremely difficult to repair Limited mechanistic understanding Limited data applicable to LWR Limited facilities & capabilities for irradiated materials R&D Prohibitively high cost associated to irradiated materials studies

Ion Irradiation Plays Complementary & Important Role Ion Irradiation Plays Complementary & Important Role Neutron irradiation provides conditions protypical to reactor core internal environments - Preferred capability to validate enginnering solutions - Retrieved in-service component expands opportunities - The capabilities is extremely limited, only a handful of facilities around the world with the right capabilities for LWR needs Expensive, long time, radiation protection, etc. Ion irradiation is a complementary irradiation tool - More suitable for mechanistic studies - Faster and more cost effective Greater flexibilities - Has its own limitations: fidelity of simulation (know-how), limited size, and much more... EPEI RESEARCH INSTITUTE \$2015 Electric Power Research Institute. Inc. All rights reserved.

Rapid Simulation of Irradiation Damage in LWR Internals at High Fluence

Rapid Simulation of Irradiation Damage in LWR Internals at High Fluence

 Objective: Develop and validate an approach based on heavy ion irradiation (Fe²⁺ or Ni²⁺) with He/H implantation for cost effective and rapid simulation of irradiation damage, with a focus on void swelling behavior, in PWR internals at high fluence

Motivation PWR Internals are expected to experience high fluence well exceeding 100 dpa at certain locations during first and second license renewal (60-80 years). There is a need for data and validated models to predict the degree of irradiation damage expected in austenitic stainless steel internals at high fluence.

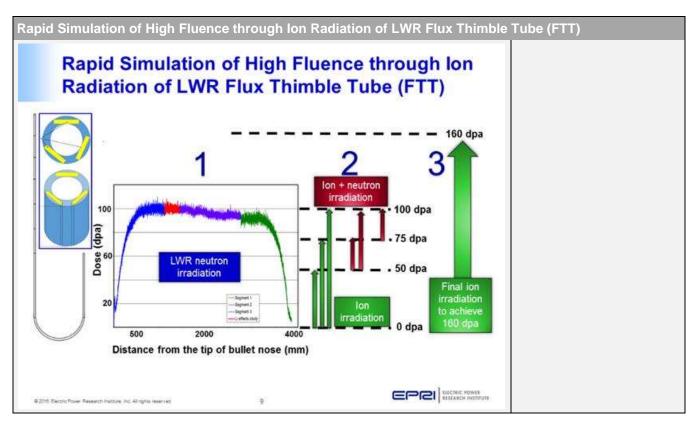
 Approach: Use the materials retrieved from an operating PWR reactor to perform ion irradiation experiment (see the next 3 slides) 1. Amounts to the re-irradiation approach previously discussed.

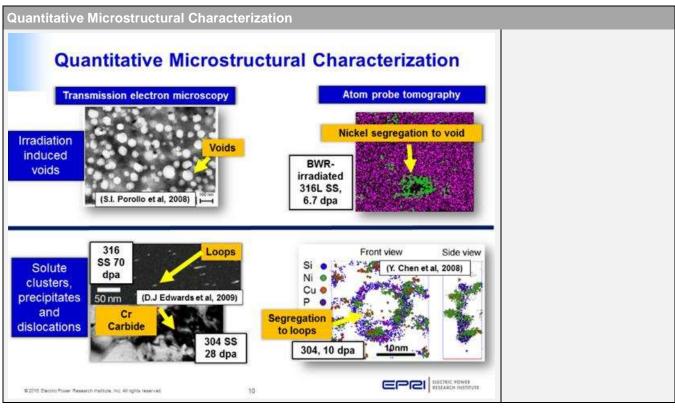
EPRI HISCING POWER HISTORY

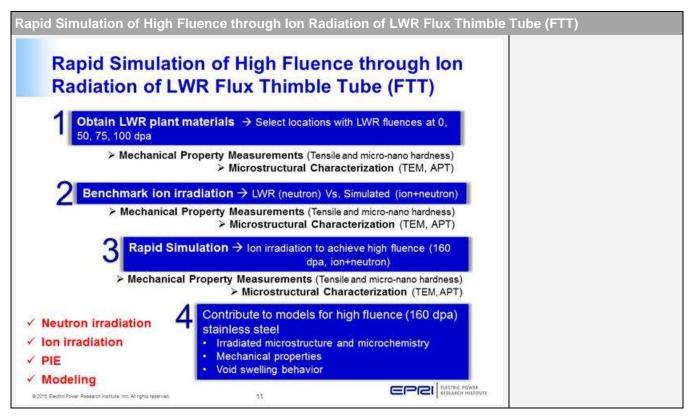
EPEI HILLER POWER

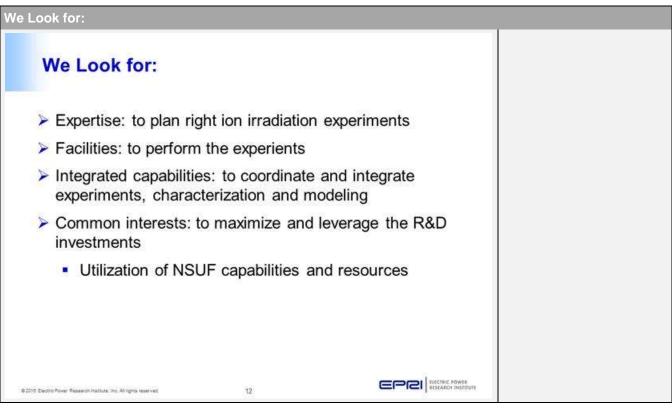
8-3012 Decim Fourt Research (rathus, Inc. A) rights reserved.

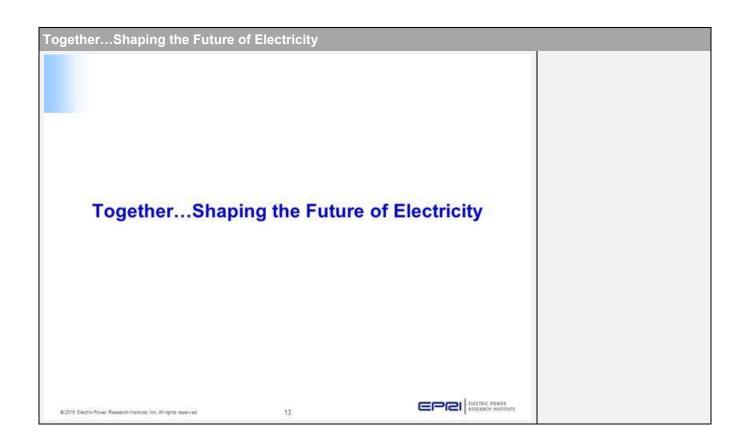
9-3012 Decreo Fourt Research Portule, Top All-Tyles meaned











Appendix E Ion Beam Facility Presentations

Appendix E

Ion Beam Facility Presentations

Presentation: IVEM-Tandem User Facility

Meimei Li





Slide 3 **Ion Irradiation Capability** Ex situ ion irradiation In situ Ion Irradiation Dual-beam, triple-beam ion irradiation capability exists, but is inactive (chamber **Beam Energy** 50 keV - 1 MeV with three beamlines, a 2 MeV Tandem H, He, Ne, Ar, Kr, Xe, and many Ion Types accelerator, an ion implanter, and a lowelements from Al to Au energy ion gun) Combine in situ and ex situ ion 1010 - 1012 ions/cm2/s Ion Flux irradiations (10-5-10-4 dpa/s) Capability for ex-situ high-dose combined ~100 dpa/day High dose with in-situ ion irradiation is being Uniform beam , 1.5 mm Ø designed, allowing a unique ability to Beam size follow material microstructural Dosimetry Real-time dosimetry with Faraday development to exceptionally high doses. cup in the microscope column High-energy, heavy-ion irradiation can be Dual-beam Add a low-energy ion gun to performed at Argonne Tandem-Linac study combined effects of He Accelerator System (ATLAS) User Facility and displacement damage (under construction). ete Baldo tunes the

Irradiation Environments and Conditions

In situ heating/cooling (20 K to 1300°C)

- Double-tilt LT stage (20 K 295 K);
- Double-tilt HT stage (20°C 900°C);
- Single-tilt HT stage (20°C 1300°C);

In situ straining

- Single-tilt HT straining stage (20°C 600°C):
- Single-tilt LT straining stage (-196°C 100°C);

Well-controlled experimental conditions

- · Controlled metallurgical variables
 - Constant specimen area
 - Crystal orientation
 - Single microstructural feature
- · Controlled irradiation variables
 - Ion type, energy
 - dose rate, dose
- · Controlled irradiation temperature

Coupling *in situ* ion irradiation with *in situ* stages for heating, cooling or straining enables studies of combined effects of irradiation, temperature and stress in real reactor environments that cannot be revealed through traditional post-irradiation examination.

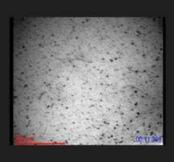


TEM Specimen Holder Vacuum Storage Station

Slide 5

In situ Real-Time TEM

- Hitachi-9000 microscope with accelerating voltage up to 300 kV (examination of thicker samples)
- High-resolution real-space imaging: point resolution of 0.25 nm at 300 kV
- Digital image recording and video recording
- Recent Upgrade installed a high-resolution, high-speed Gatan OneView camera
 - Time resolution 5ms (frame rate increased from 15 frames/sec to 200 frames/sec)
 - Image resolution increased to 4kx4k

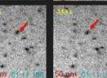










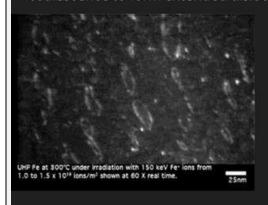




Cascade defect (dislocation loop) formed by single ion impact even between 0.089 and 0.084 sec

What Distinguishes IVEM-Tandem from Other Ion Irradiation Facilities: In situ, real time imaging to track individual nm-sized defects during Irradiation

In situ movie shows irradiation defect formation, motion, and coalescence to form extended dislocation structure.



11 video files included in the publication revealed:

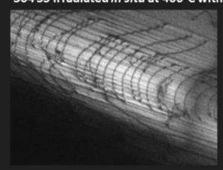
- One-dimensional hopping of small dislocation loops
- Dislocation loops with BV= <111> highly mobile in direction of BV.
- Dislocation loops with BV <100> sessile.
- Loop hopping was much less common in Fe-Cr alloys
- Some formed over 0.2 sec consistent with cascade overlap mechanism.
- Dislocation loop coalescence in string alignment.
- Temperature dependence, only <100> loops at ≥500°C.

M.Hernandez-Mayoral, Z. Yao, M. Jenkins, M. Kirk, "Heavy-ion irradiations of Fe and Fe-Cr model alloys Part 2: Damage evolution in thinfalls at higher doses," Phil Mag 88(21), 2881 (2008).

Slide 7

Unique Experiment – Defect and Dislocation Interactions under Irradiation+Temperature+Load

304 SS irradiated in situ at 400°C with 1 MeV Kr ions to dose of 3x1013 ions/cm2.



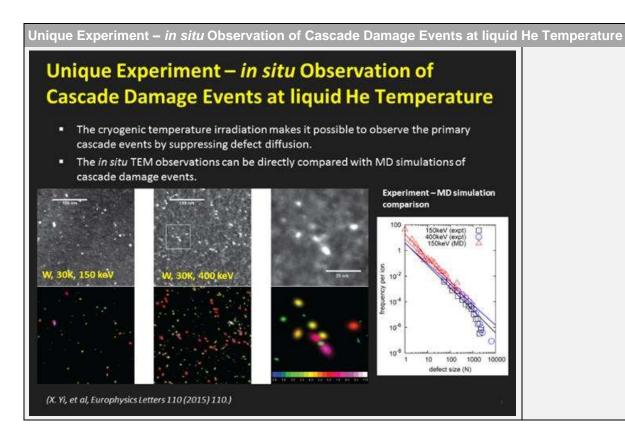


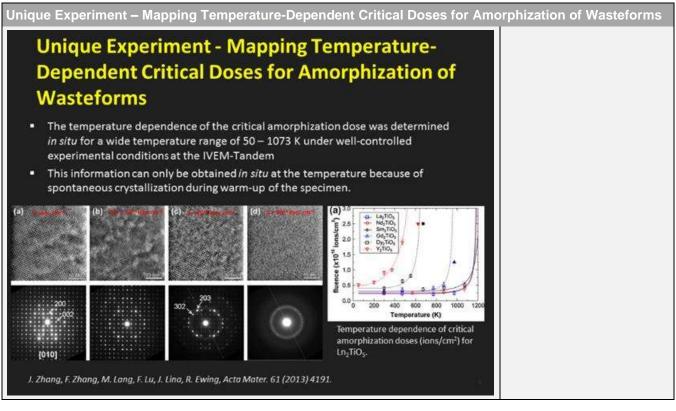
Without ion irradiation

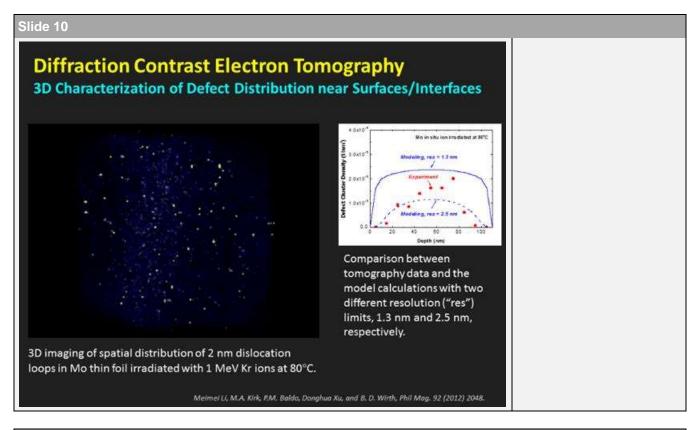
With ion irradiation

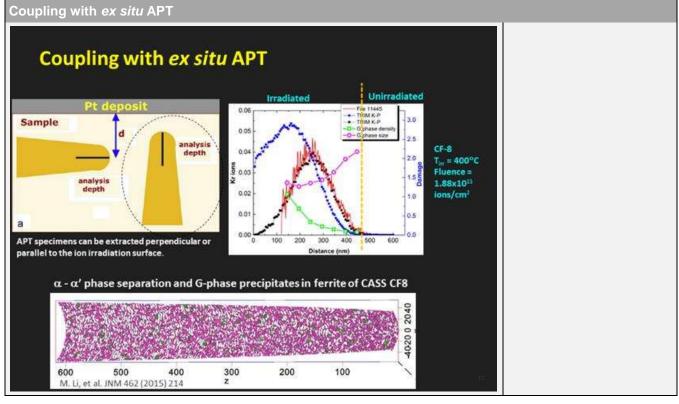
- Direct insight to the mechanisms by which dislocations interact with and annihilate radiation defects to create channels, dispelling some of the common held beliefs about the processes and mechanisms.
- New insight as to how strain is transferred across grain boundaries in irradiated metals, the results of this effort have identified the deterministic step in irradiation stress corrosion cracking.

J. Kacher, I. M. Robertson, Acta Mater. 60 (2012) 6657. M. Briceño et al., J. Nucl. Mater. 409 (2011) 18.









Radioactive Materials Handling

- Radioactive samples have been irradiated at the IVEM-Tandem
 - Low-dose neutron-irradiated steels
 - Nuclear fuels: U, U-Mo, UO2, etc.
- Irradiated Materials Laboratory (IML)
 - A radiological Facility in the same building
 - Electro-polishing (Tenupol-5) of radioactive TEM specimens in IML
 - Argonne Nuclear Engineering Division operates both IVEM-Tandem and IML
- Radioactive material characterization using synchrotron X-rays is routinely carried out at the Advanced Photon Source

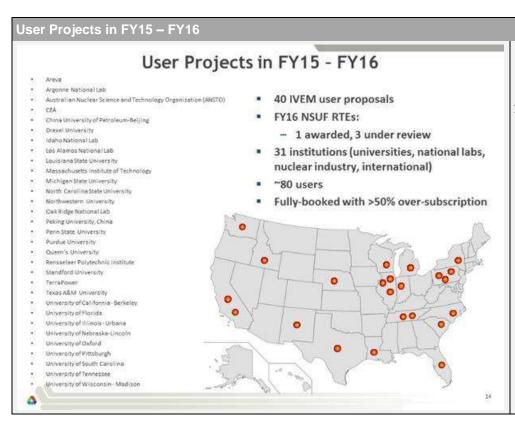


Facility History and Current Status

Facility History and Current Status

- The 1st generation, HVEM-Tandem user facility was commissioned in 1981 in Materials Science Division, ANL, supported by DOE BES.
 - A high-voltage electron microscope (HVEM) interfaced with two accelerators (2 MV tandem and 650 kV ion implanter).
- The 2nd generation, IVEM-Tandem was commissioned in 1995, and was part of Argonne's Electron Microscopy Center supported by DOE BES until 2014.
 - Increased imaging spatial resolution by nearly one order of magnitude
- DOE NE and ANL signed Memorandum of Agreement in May 2014 for full time operation of IVEM-Tandem to support nuclear energy research.
- The Facility was transitioned to Nuclear Engineering Division, ANL in June 2014.
- In FY 2016, the IVEM-Tandem received 50% DOE NE support through NSUF.





- 1. Can IVEM operate longer hours if funding was expanded?
- 2. With sufficient staff support, it can operate longer hours.

User Research

User Research

 All user projects are nuclear related. A majority of user projects are funded by NEUP, supporting FCRD, ART, NEAMS, NEET programs. User projects have also been funded/performed by nuclear industry (e.g. EPRI, TerraPower, Areva).

DOE Labs DAlversities DOE Labs Industry International Staff

User Research Areas

- Fundamental understanding of defect dynamics under irradiation, temperature and stress
- Validation and verification of computer modeling and simulations of radiation damage
- Developing advanced radiation-resistant nuclear fuels, cladding and structural alloys, and waste storage materials
- Developing advanced accident tolerant materials and fuels
- Developing new material design concepts, e.g. nanostructured materials, high-entropy materials, for enhanced radiation resistance

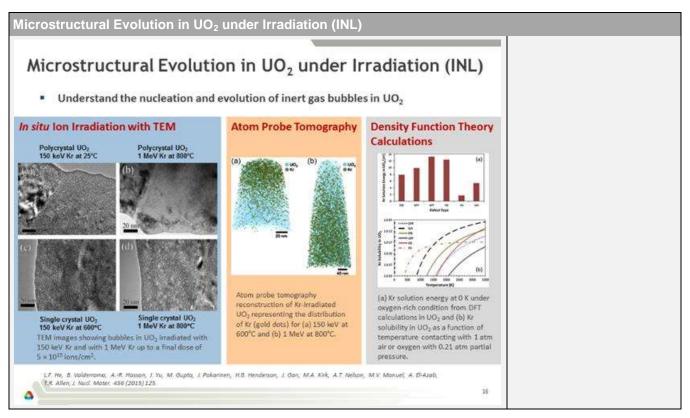
High Productivity

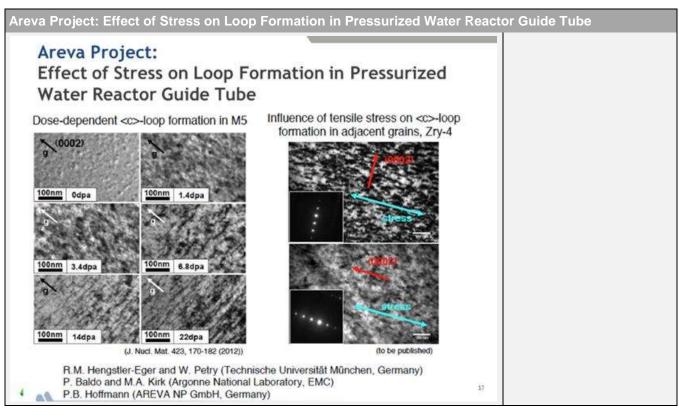
4

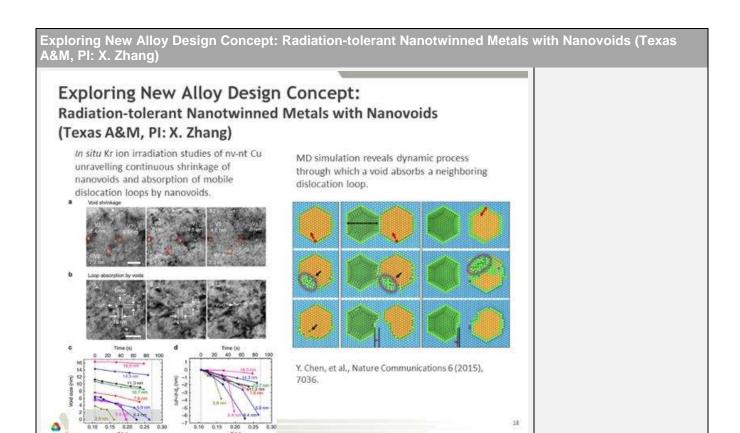
- > 100 publications in the past four years; many of them are published in premier scientific journals with high impact, e.g. Nature, Science
- Numerous invited and contributed talks at national and international meetings

Education and Training

~30 PhD student theses in 4 years based on research conducted at the IVEM-Tandem



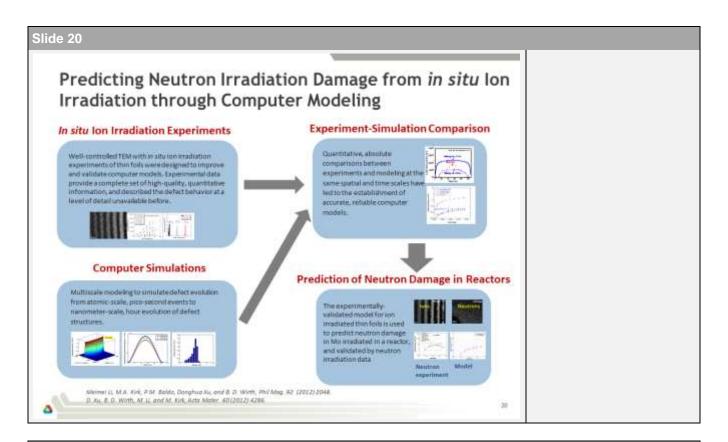




Support Verification and Validation of Modeling and Simulation

Support Verification and Validation of Modeling and Simulation

- Many experiments at the IVEM-Tandem are performed to benchmark computer models designed to simulate both ion and neutron irradiation damage;
- Experiments are carried out under highly-controlled conditions that allow producing high-quality data for single-mechanism studies or studies of collective behavior
- In situ TEM observation of heavy ion irradiation damage reveals cascade damage
 phenomena, e.g. single cascade events, cascade cascade or cascade subcascade
 interactions, cascade defect production and annihilation rates, and the experimental data
 can be directly compared with molecular dynamics simulations of cascade damage.
- In situ ion irradiation can access the full history of the kinetic development of the
 defect structure under irradiation, providing critical input into the computer models of
 microstructural evolution during irradiation that determines the lifetime of materials in
 nuclear systems.
- The high-quality experimental data obtained at the IVEM-Tandem Facility provided useful
 data for validating the nuclear materials and fuels models being developed under the DOE
 Consortium for Advanced Simulation of Light Water Reactor (CASL) and the
 Nuclear Energy Advanced Modeling and Simulation (NEAMS) programs.



Summary

4

Summary

- TEM with in situ ion beam irradiation coupled with computer modeling and simulation provides a new way to understand radiation effects, critical to the development of new high-performance materials and predictive models to reliably forecast material component lifetimes in a nuclear reactor environment.
- The IVEM-Tandem Facility is a world-class facility for in situ study of defect dynamics in nuclear reactor materials, fuels, and waste storage materials. User projects support DOE NE's FCRD, ART, NEAMS programs and nuclear industry needs.
- Given the great scientific impact of the IVEM-Tandem research to advance the DOE-NE missions, the high productivity of its users, its importance to education and training of next-generation scientists and engineers, and the potential for future growth, support for the IVEM-Tandem as a user facility should be a priority investment for the DOE Office of Nuclear Energy.

Support Letters from the Community

Support Letters from the Community

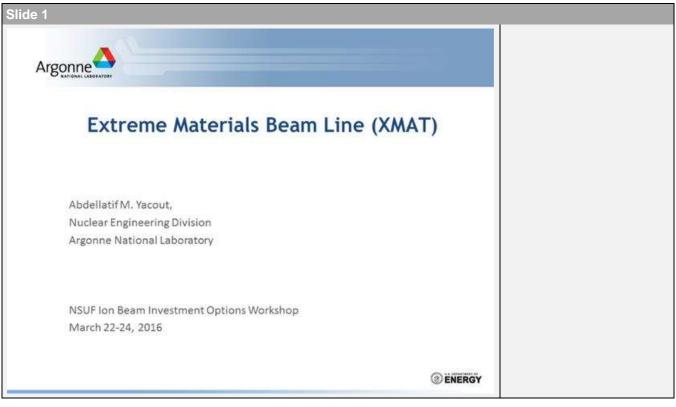
- Stuart A. Maloy, Los Alamos National Laboratory
- T.-L. (Sam) Sham, Argonne National Laboratory
- Tiangan Lian, Electric Power Research Institute
- Rosmarie HENGSTLER-EGER, AREVA
- Arthur T. Motta, Penn State University
- Brian Wirth, University of Tennessee
- James F. Stubbins, University of Illinois at Urbana-Champaign
- Ian M. Robertson, University of Wisconsin Madison
- Jian Gan, Idaho National Laboratory
- Michael Nastasi, University of Nebraska Lincoln
- William J. Weber, University of Tennessee
- Mitra L. Taheri, Drexel University
- Djamel Kaoumi, University of South Carolina
- Xinghang zhang, Texas A&M

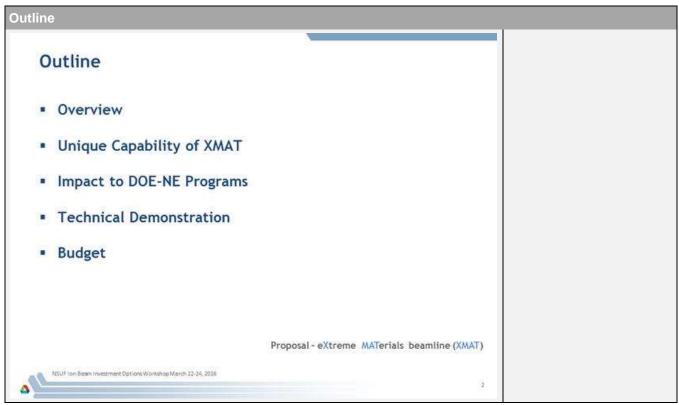
Δ

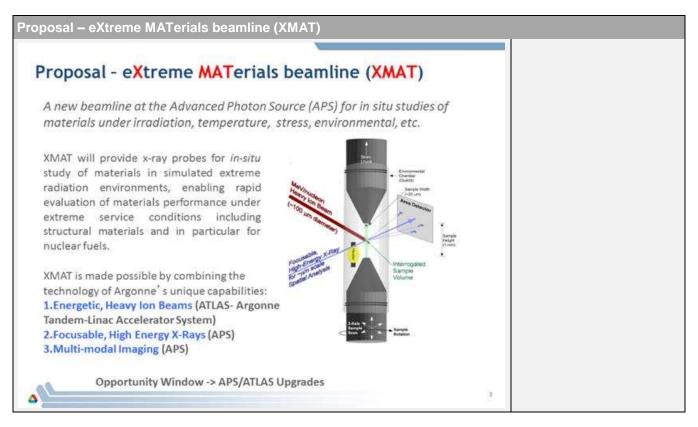
- 6

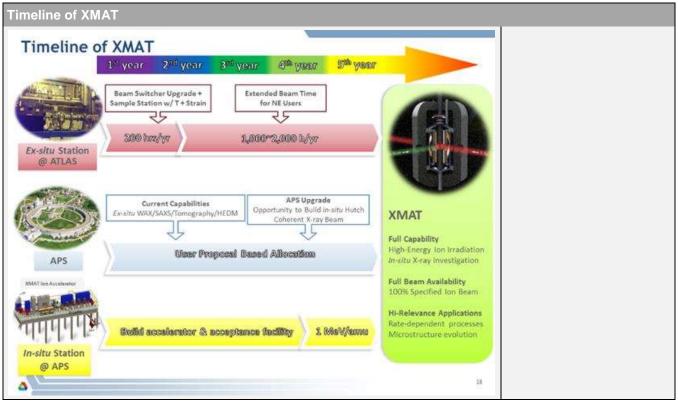
Presentation: Extreme Materials Beam Line

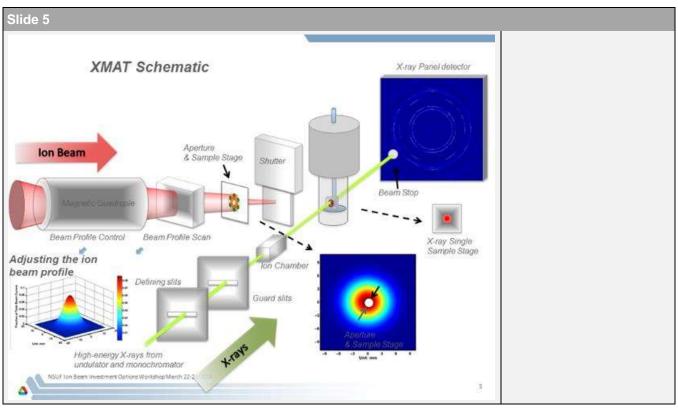
Abdellatif Yacout

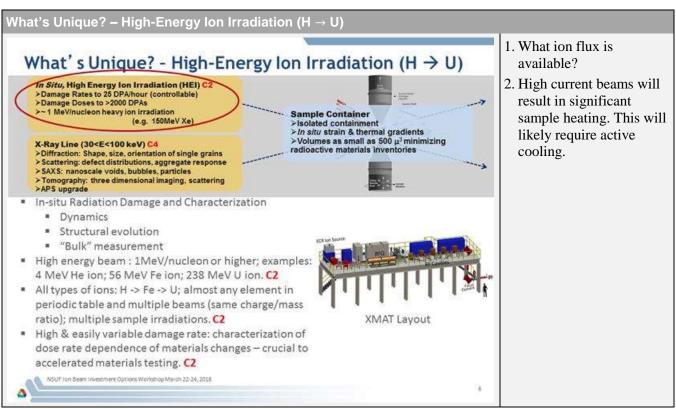


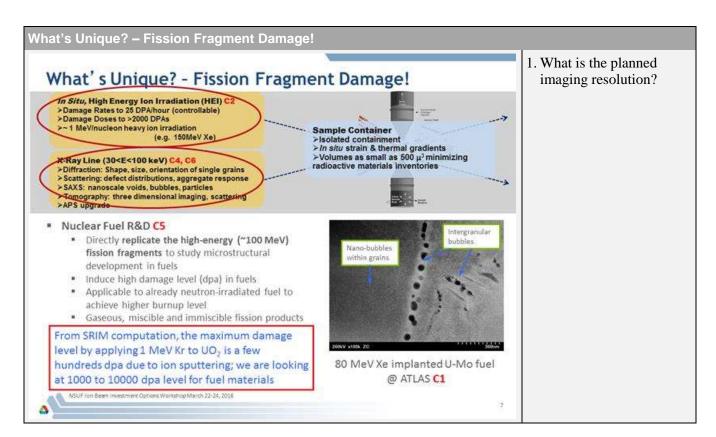


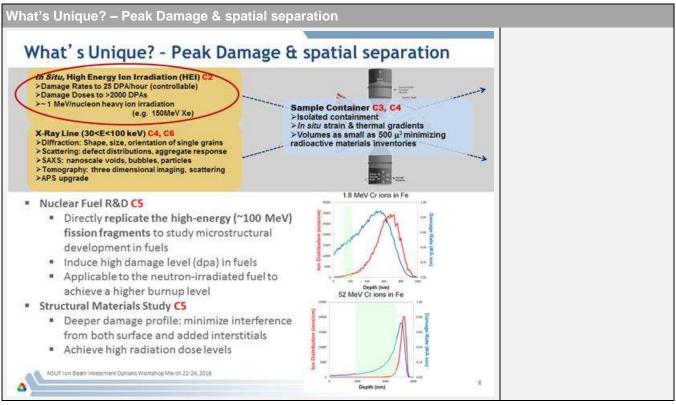


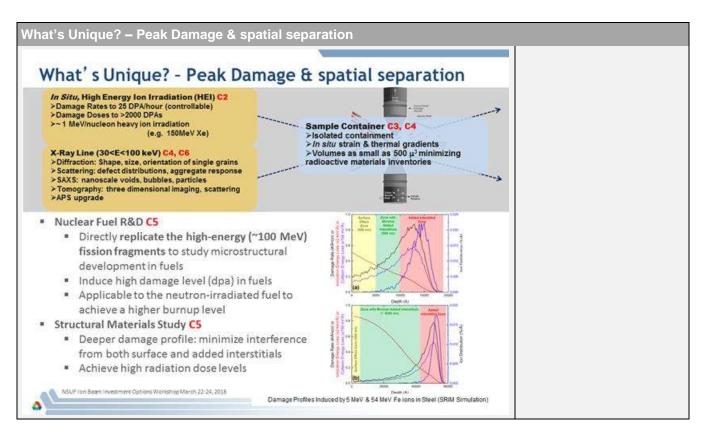


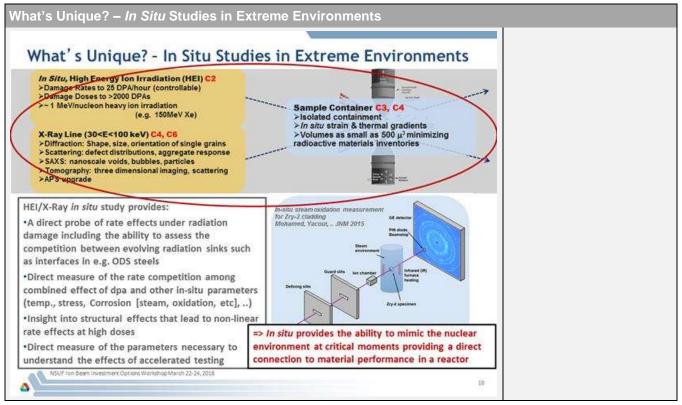












Impact on NE Research Programs C5

Impact on NE Research Programs C5

- Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program:
 - Support fuel and cladding model development and validation for NEAMS codes (e.g., MARMOT code) – single effects:
 - Microstructural evolution, e.g., grain growth, fuel gas & bubble mobility, bubble resolution, recrystallization (HBS rim), ...
 - In-situ characterizations provide key kinetic data on nucleation, diffusion & growth, and 3D structural evolution (temp, stress, dpa,..)
 - Modeling new fuel & cladding material behavior; e.g., USi for ATF (ATF-HIP), advanced structural alloys to high dpa.

Advanced Fuel Campaign (AFC):

- Accelerate development of high burnup metallic fuel & advanced LWR fuel (USi, UMo, ...) through emulation of fission fragments damage to high burnps (1000's dpa) and associated gas accumulation and release
- Transmutation fuel (4MeV He to emulate a decay & transmutation+100MeV Xe, I, ...); inert matrix fuel with fission fragments damage in both fuel and inert matrix materials

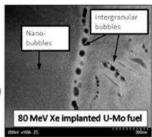
ARC and LWRs Programs:

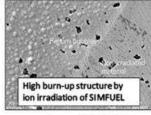
- Advanced structural materials R&D (ARC); high dpa, in-situ bulk characterization (stress, temperature, dpa)
- Pressure vessel materials, high burnup UO2 (LWRs)

Waste Management:

Effects of radiation damage on waste form-4MeV He

NSUF Ion Beam Investment Options Workshop March 22-24, 201





Baranov, JNM, 452, 2014

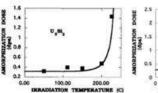
1. How do you control beam heating when producing high burnup structure?

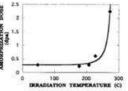
Applications to Oxide and Silicide Fuels C5 Applications to Oxide and Silicide Fuels C5 Defect Evolution in Uranium Dioxide: Emulate ~1 MeV/amu fission fragment energy

- Use low energy noble gas (Xe, Kr) ions to implant
- gas atoms; use high-energy (~1 MeV/amu) solid fission products (Zr, I) ions
- Replication of defect structures observed in in-pile irradiated fuels

Amorphization Threshold of Silicide Fuels

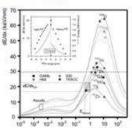
- In situ investigation of the amorphization threshold at low temperatures using IVEM-Tandem
- This dynamic process takes place at low dose and can hardly be captured in in-pile irradiated fuels



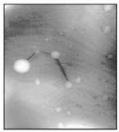


Amorphization threshold of U₃Si₂ and U₃Si by in situ ion irradiation (Birtcher, 1996&1997)

NSUF Ion Beam Investment Options Workshop Merch 22-24, 20

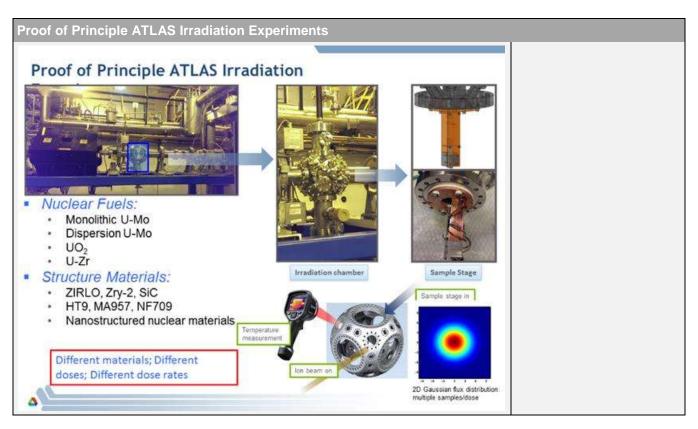


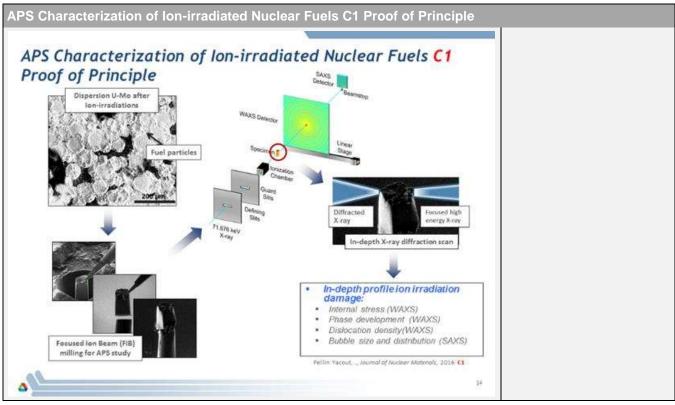
Energy domain of fission fragments and correspondin energy loss rate in UO₂ (Matzke, 2000)

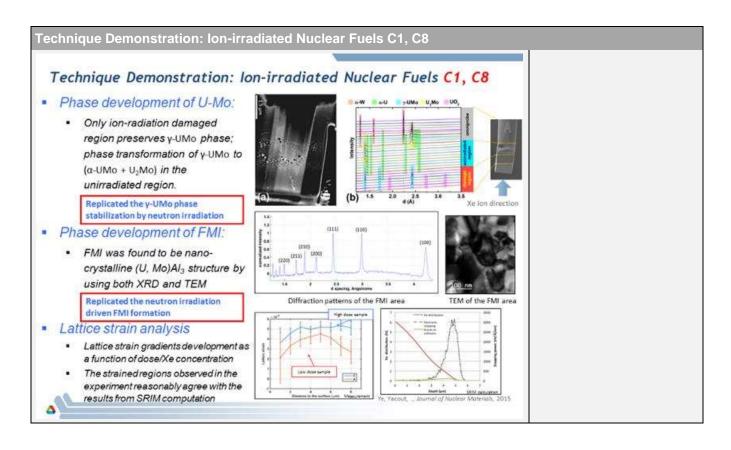


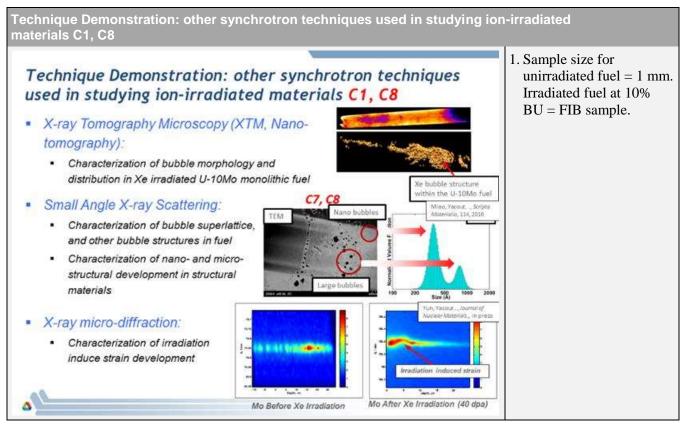
Gas bubble formation induced by 40 keV Kr implantation and 72 MeV I irradiation in UO₂ (Matzke, 2000)

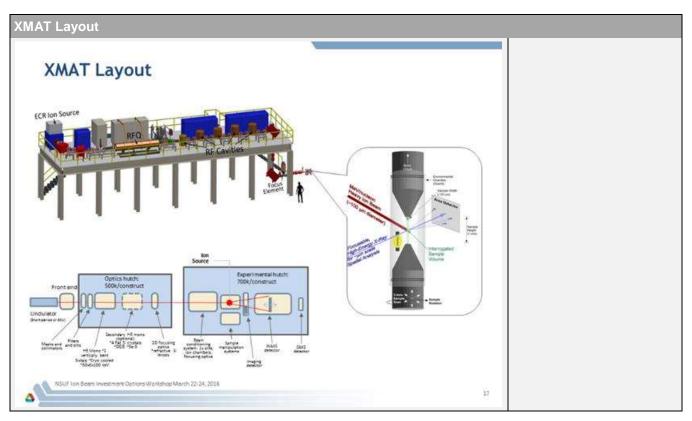
Li

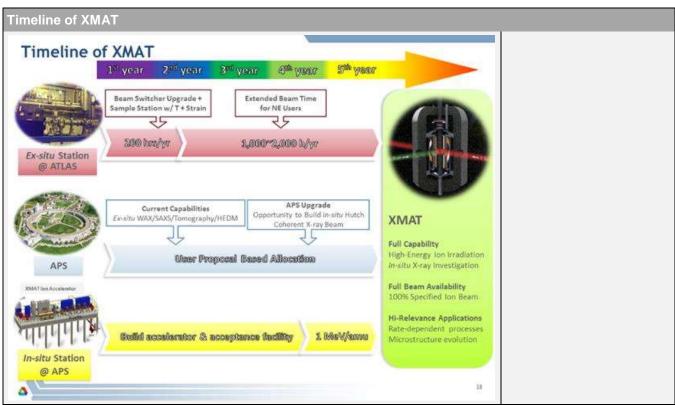












XMAT Schedule and Cost

XMAT Schedule and Cost

A phased approach allows achieving an operating system within the first year. Initial operation would allow irradiation at ATLAS (200 hrs first year, 30% of operational days within the two years). In situ operation at APS would come online as the APS upgrade is completed (5 years).

		Description	Achieves	Costs
Year 1	Phase 1	Design & Build multiuser beam switcher at ATLAS and irradiation station	Full beam capability for 30% of yearly operating hours for NE programs - (Until complete 200 hrs of beam time will be allocated)	\$2M (ANL contributes \$0.5 M for design)
	Phase 2	Begin XMAT full accelerator design for APS		\$2 M
Year 2	Phase 1	Complete & Test	Full beam capability for 30% of yearly operating hours for NE programs (ex situ)	\$1 M
	Phase 2	Begin acquisition and testing of accelerator components		\$3 M
Year 3-5	Phase 1	Ex Situ Irradiation Facility operates for 30% of yearly operating hours (~2400 hrs of beam time for NE programs)		\$1M /yr
	Phase 2	Complete operation as part of APS-U beam line	Full in-situ analysis under APS user program + 100% irradiation time	\$3 M / yr
			Total Cost Build Cost	\$20 M
Out year operational Costs		ATLAS facility ceases operation	lon source 1 man year, 3 man year user support & x-ray	\$1.5 M/yr

19

Key XMAT Advances

Key XMAT Advances

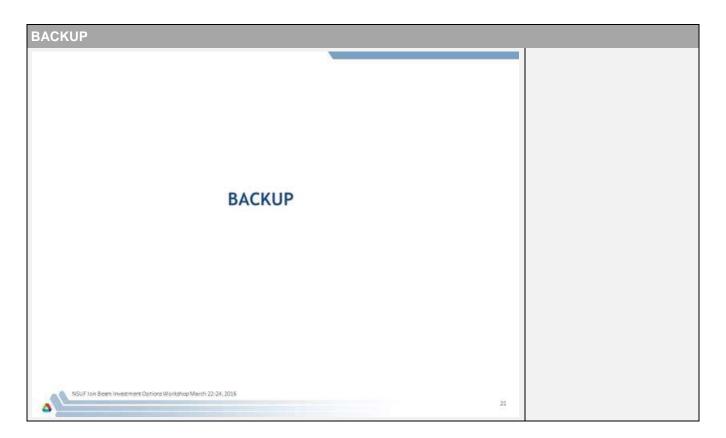
In comparison to most existing ion irradiation capabilities, the XMAT ion energies and currents are ~100 times higher. The increased ion irradiation energy (e.g., 133 MeV for xenon) enables several critical advances:

- It provides a unique opportunity to simulate the effects of fission fragments in nuclear fuels, where ions of all elements can be accelerated to fission fragment energies, while being characterized in situ.
- For cladding and structural materials, the increased penetration depth of energetic ions allows
 the "bulk behavior" to be examined, eliminating surface-sink effects, and allows understanding
 of individual physics of ion damage including electronic, collisional, & added interstitial
- The in situ penetrating ability of the APS focusable hard x-rays, applied during ion irradiation, is another key advancement of XMAT that allows the interrogation of individual grains within solid material samples during irradiation.
- With this information and related computational modeling, the differences between ion and neutron irradiation as well as the impact of fission products damage become much more understandable.

XMAT can close the design loop for the nuclear materials community in two ways:

1)It provides accelerated testing for hundreds of samples (24; 7)

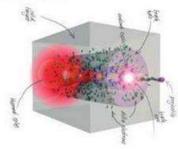
2)It reveals the key "single" physics dependences required for accurate computational modeling



Nuclear Waste Forms

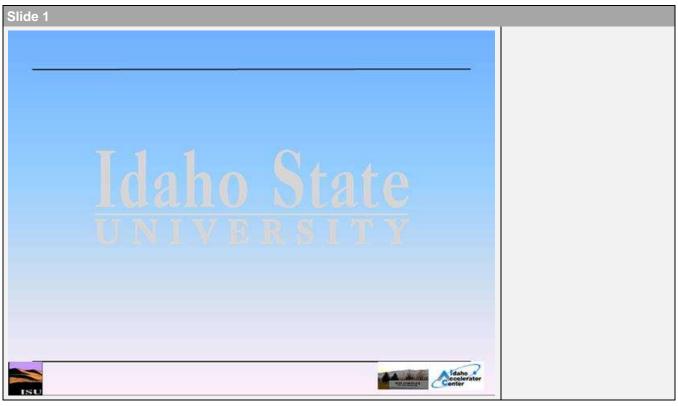
Nuclear Waste Forms

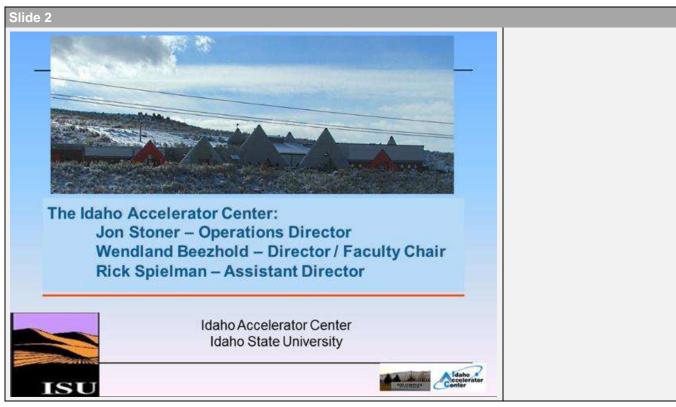
- Radioactive decay in waste form materials heats typical structures to ~100 C.
- This temperature is reached in a complex way as alpha particles electronically
 excite waste form materials resulting in high temperatures along 10 nm diameter
 cylinders with heights extending to 15 microns.
- These cylinders after the passage of the alpha have 20% lower density and many dangling atomic bonds.
- The effect of this radiation on important waste form properties (diffusion, leaching and corrosion) has not been detected, in part, because percolation – the overlap of these tracks – will not occur for many decades.
- XMAT allows an understanding of the effects (diffusion, leaching and corrosion) on individual tracks.
- Theory can then be used to accurately extrapolate to decades and centuries.

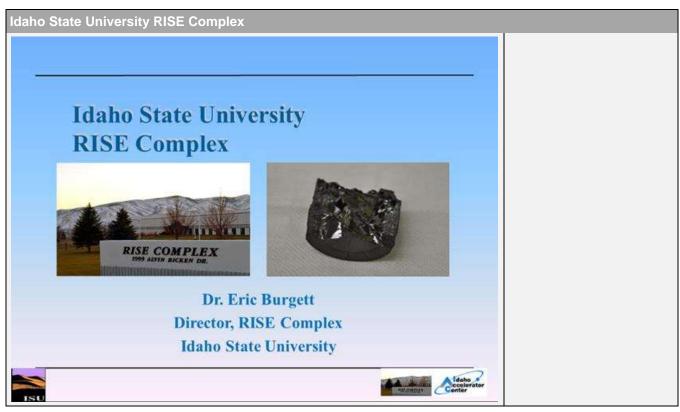


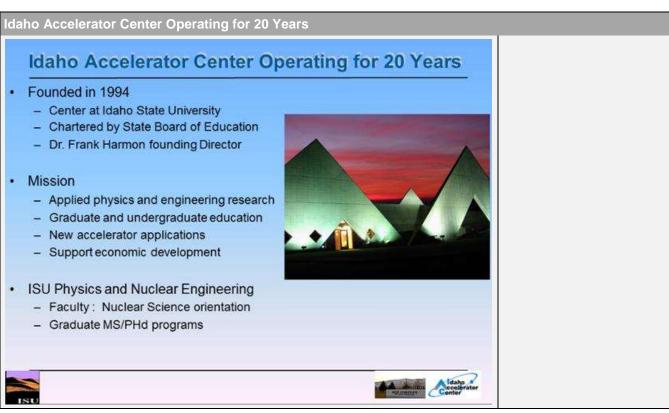
Presentation: Capabilities at the Idaho Accelerator

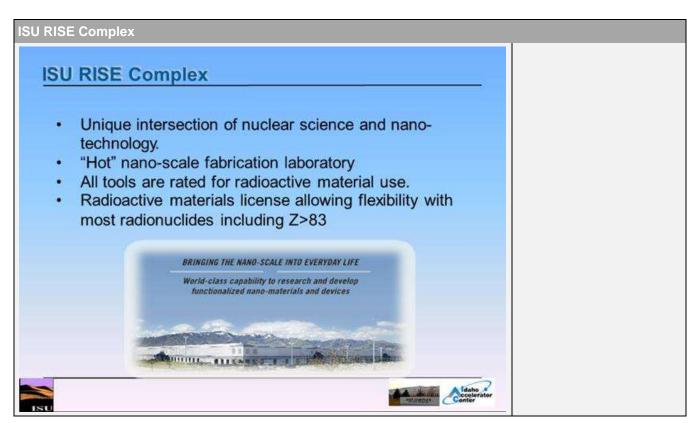
Jon Stoner

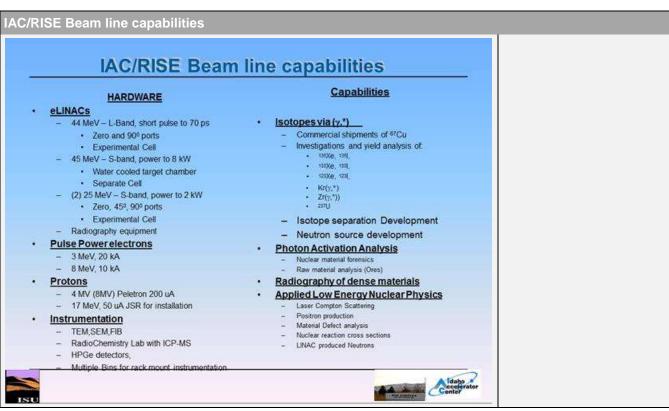


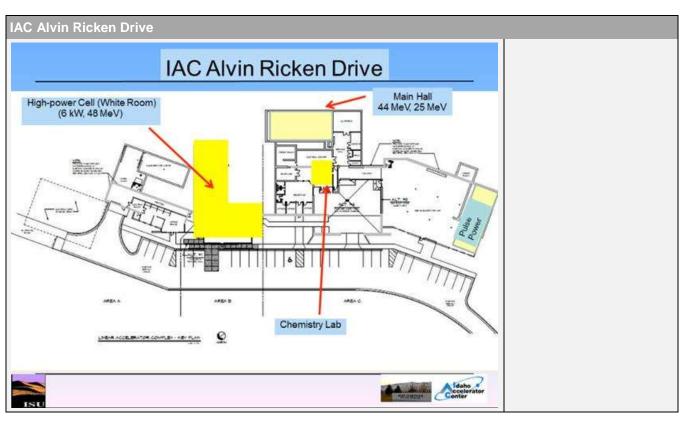


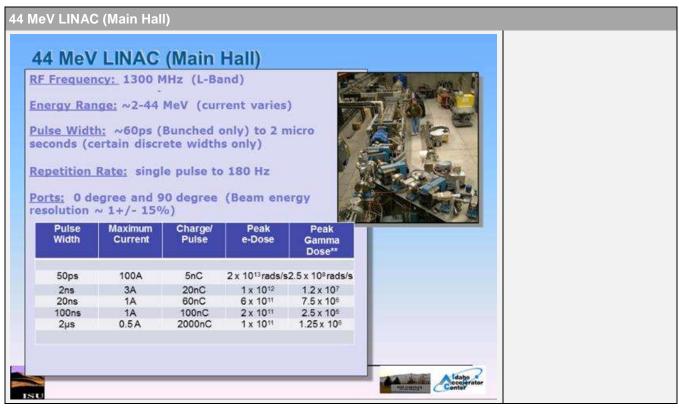




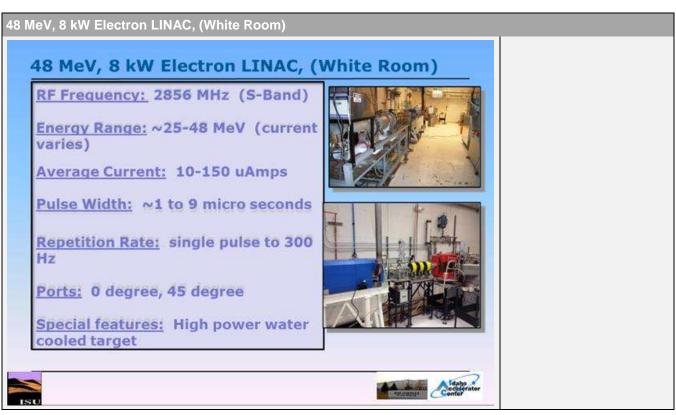




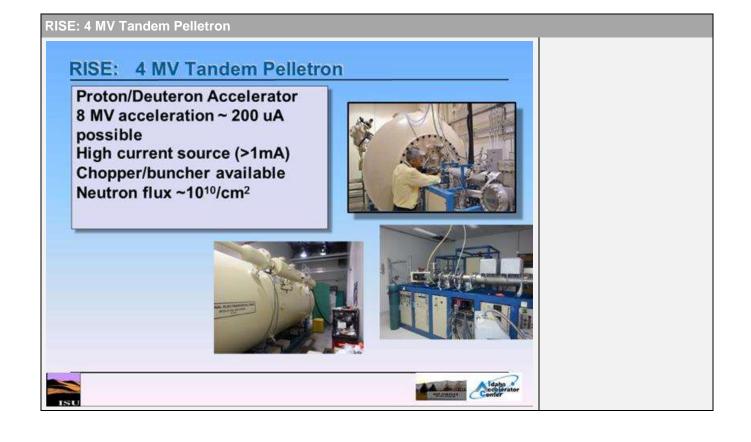


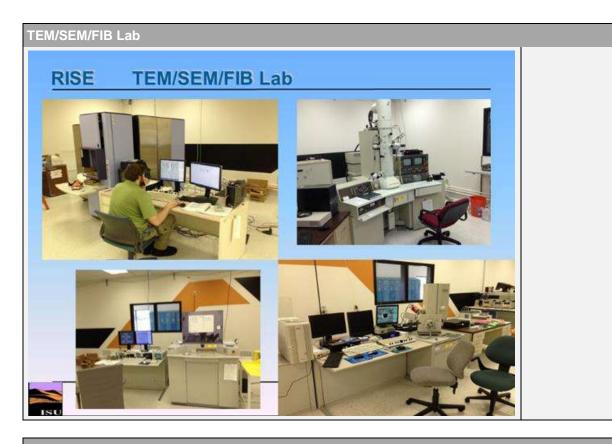


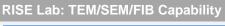




Tri-Mev Pulse Power Accelerator •Energy: 1-3 MV •Pulse width: ~20 ns •Rep Rate: ~1shot/3-5 minutes •Instantaneous current: ~18-30k Amps Applications: Radiography, Dose Rate Effects







RISE Lab: TEM/SEM/FIB Capability

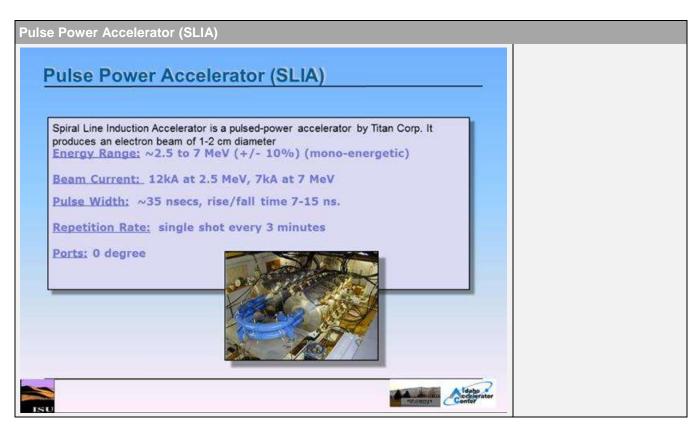
- 8" FEI FIB with high current column
 - Pt deposit, IEE
 - Nano Secondary Ion Mass Spectrometer (Dynamic nanoSIMS)
- 8" FEI Dualbeam FIB with high current column and cold FEG imaging
 - Omniprobe nanomanipulator
 - **Energy Dispersive Analytical X-Ray** spectroscopy
 - Pt, W deposit
 - 3D imaging
- FEI ESEM cold FEG XL-30
 - Hot (1200 C) and cold (77K) stages
 - Electron Back Scatter Diffraction
 - Energy Dispersive Analytical X-Ray spectroscopy
 - **EBIC** spectroscopy
 - Dynamic straining and bending stage

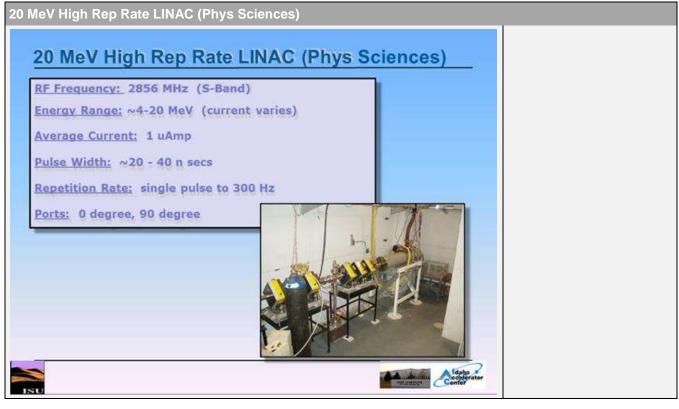
- · AMRAY analytical SEM
 - In-situ localized heating (Laser)
 - Heated stage, dynamic straining stage
 - EDAX
- · 200 kV digital imaging STEM (0.17 A resolution) Lorenz lens
 - Heated and cooled stages (1600 C 77
 - BSD STEM imaging
 - In-situ dynamic laser heating
- 100 kV digital imaging TEM
- X-ray microscope (300 nm resolution)
 - · Materials discrimination capability

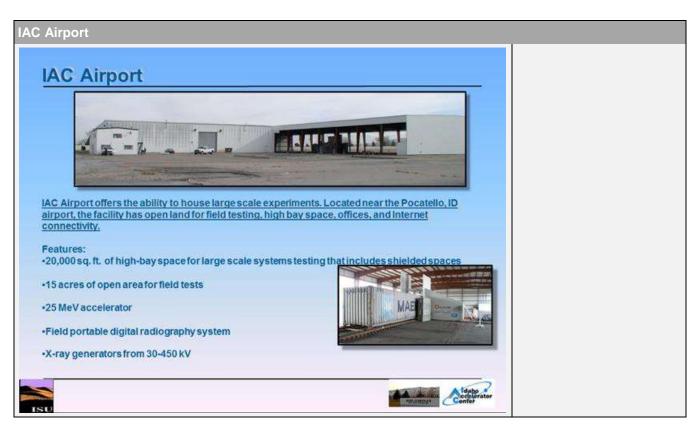


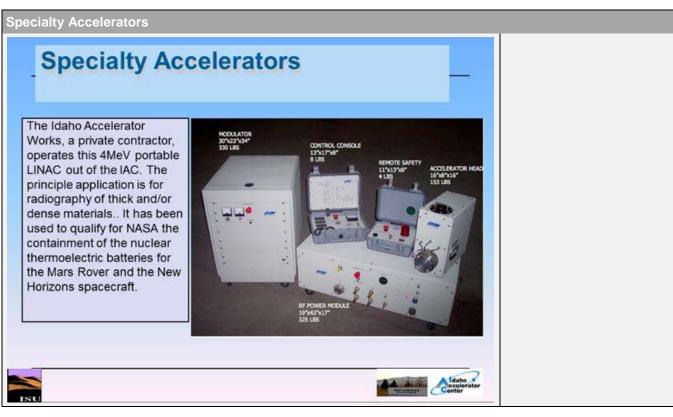
1. Can you also handle actinides?

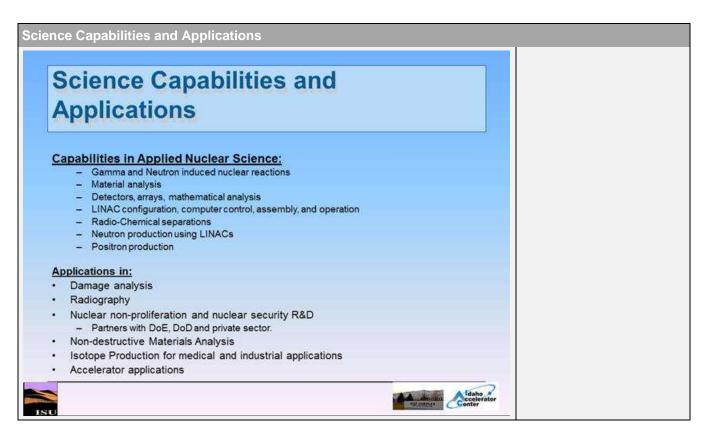


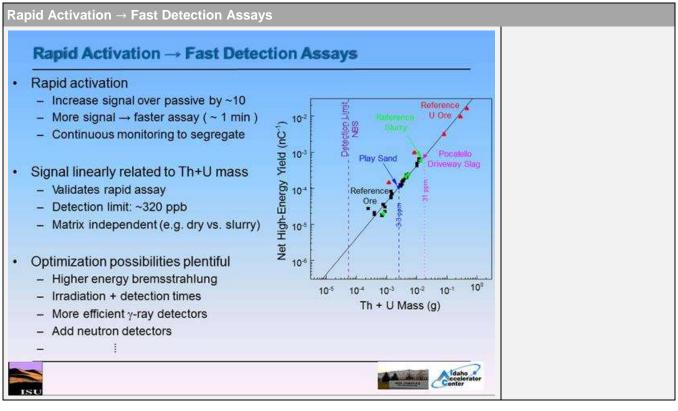


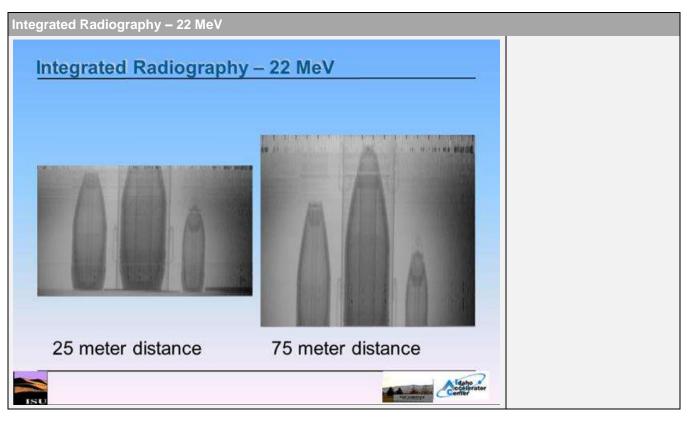


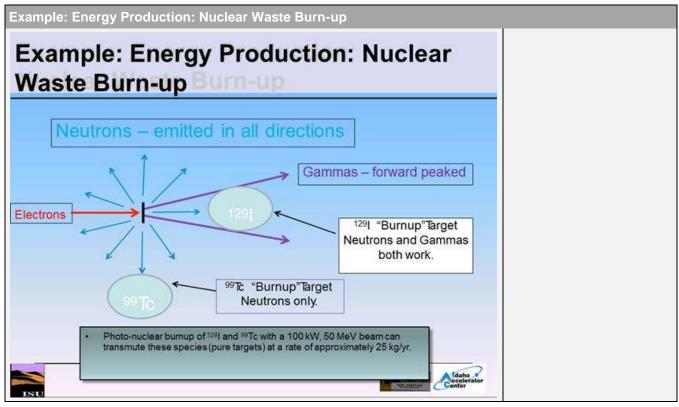


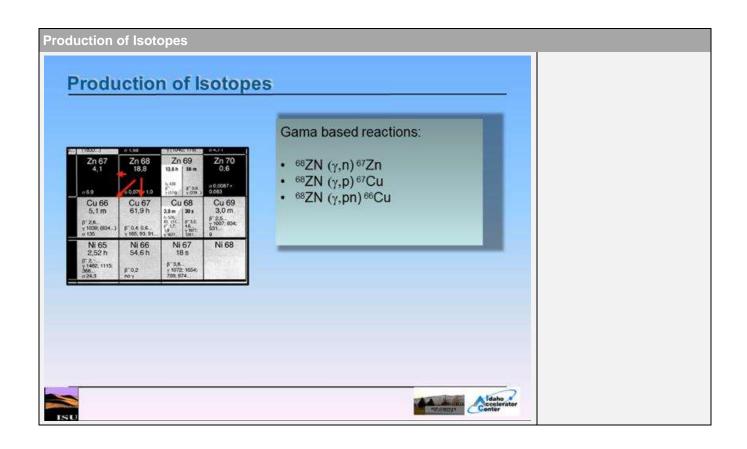






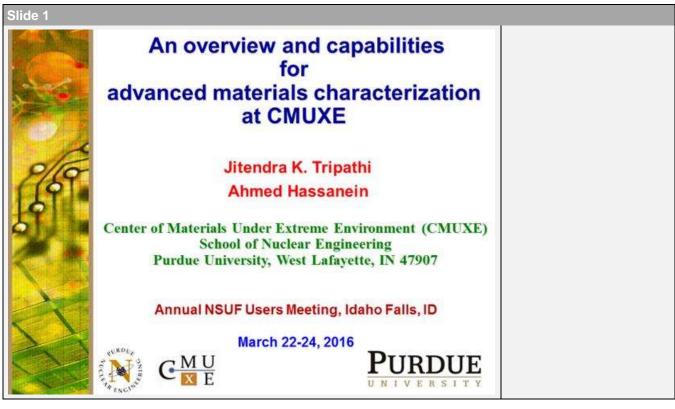


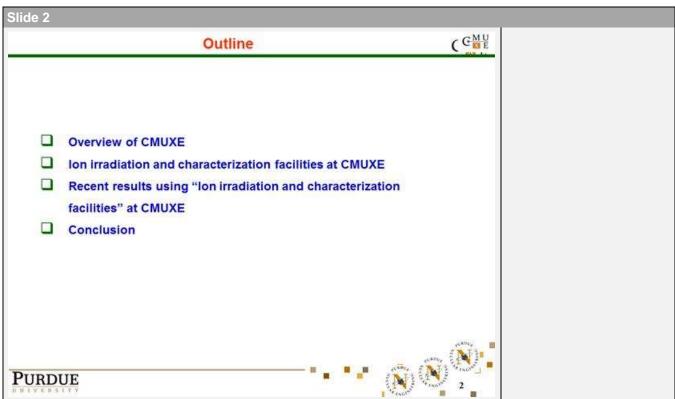


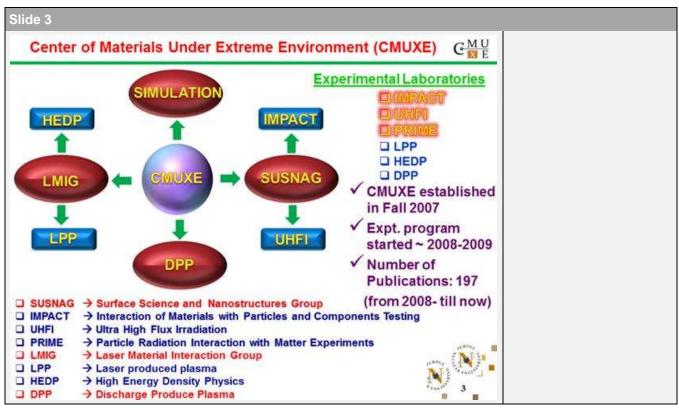


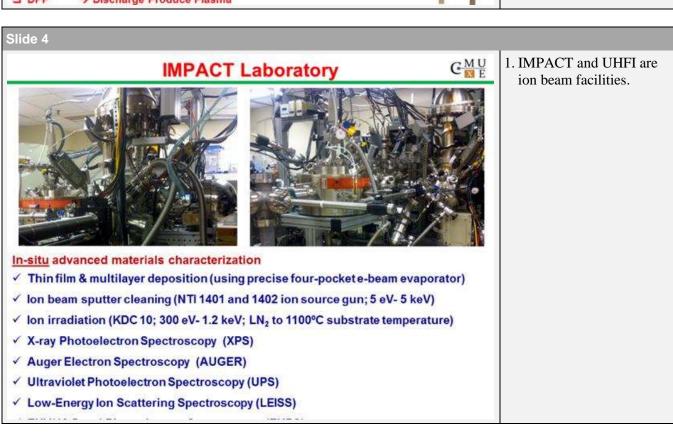
Presentation: CMUXE, Purdue University

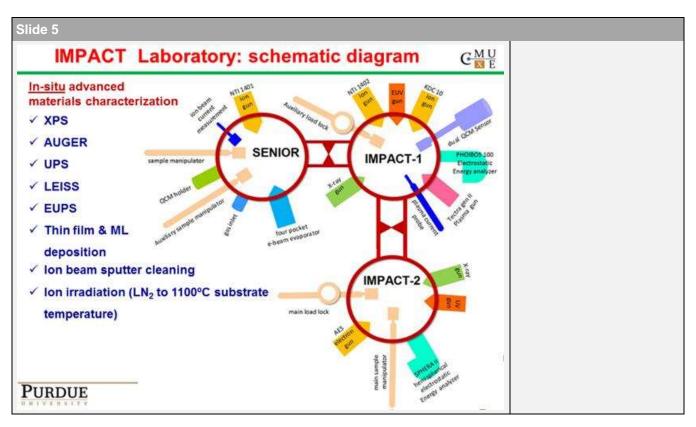
Jitendra Tripathi

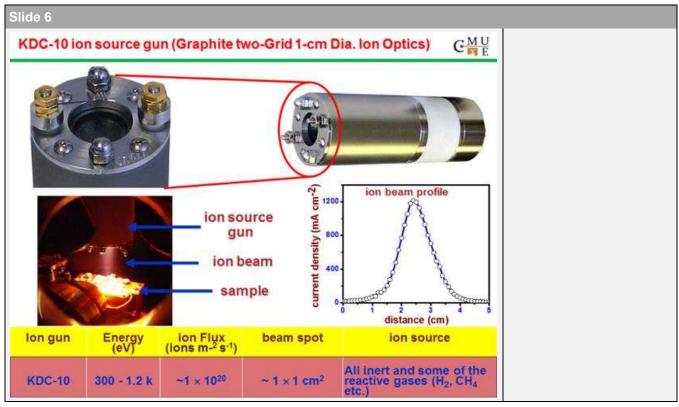


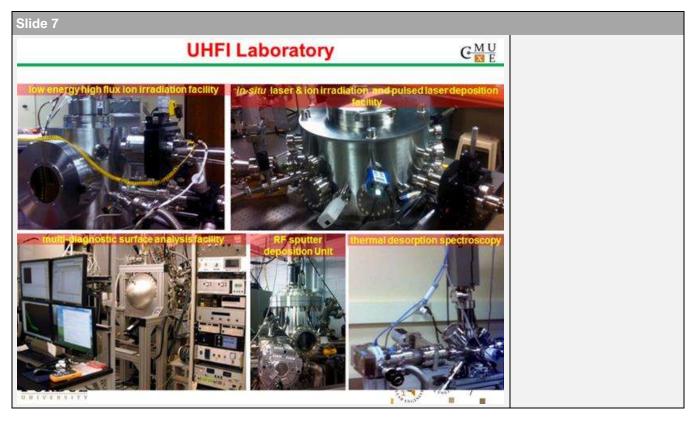


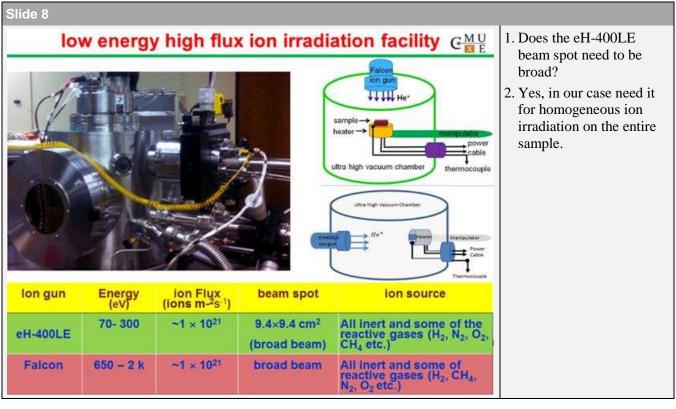


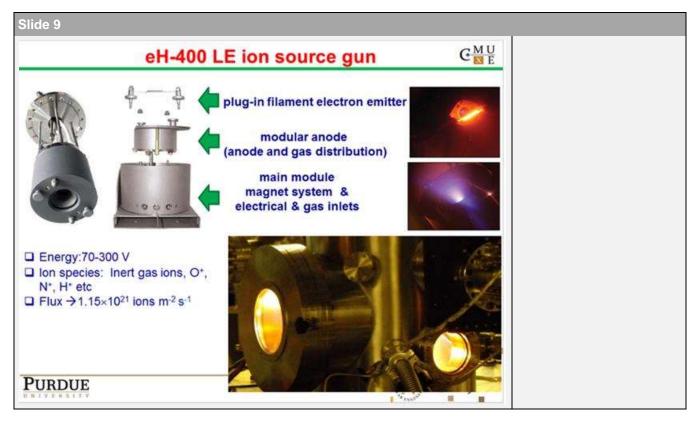


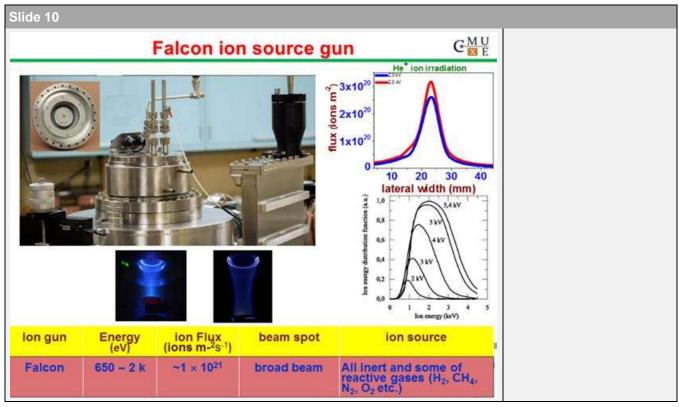


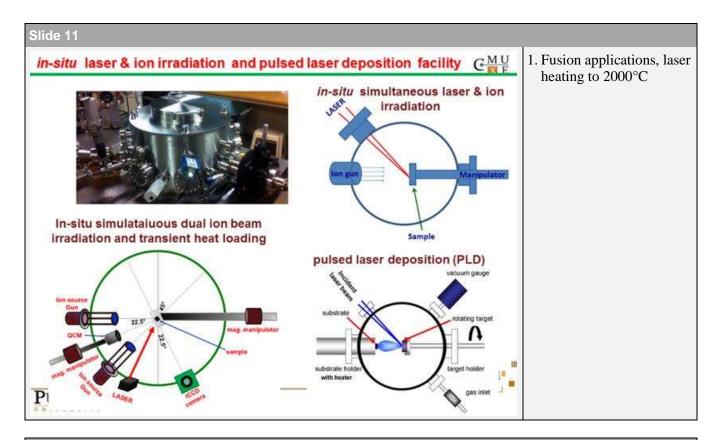


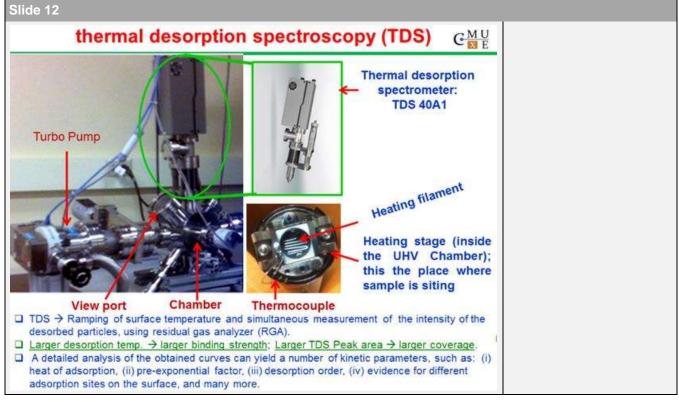








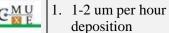


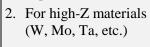


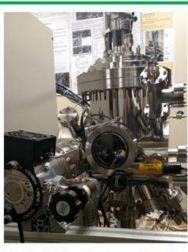
Slide 13

RF sputter deposition facility



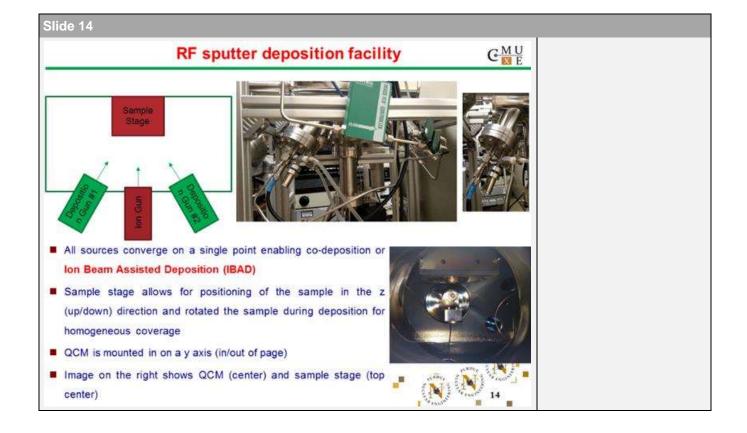








- Mantis RF Sputter Deposition Guns: [0-300 watts (RF); Non-ferrous materials; 1 in. sputter target]
- 1 Mantis RF Ion Gun: 0-600 watts (RF)
- Currently capable of running two sources simultaneously
- Film deposition (tested successfully): Ni, W, Co (couple of micro meter thick layers)



Slide 15

surface morphology and optical property measurement facility











- 1. Also has associated user facilities with TEM, S/TEM, etc.
- 2. Also has access to use the USER facility at BNC (Birck Nanotechnology Center), Purdue University (partial list, closely related to this workshop): With stateof-the-art fabrication and characterization facilities, highly qualified personnel with expertise in design, fabrication, packaging, and characterization, the BNC is the place to work on the development of new systems and technologies. A partial list (related to this workshop) of the research activity at BNC is as follows: (i) Nanoscale Metrology: Scanning Probe Microscopy (SPM), STM, AFM, Field Emission (FE)-SEM, TEM, in-situ TEM, XRD, XPS, AES, **Electron Energy Loss** Spectroscopy (EELS), ISS, Low Energy **Electron Diffraction** (LEED), Focused Ion Beam Imaging (FIB), Raman Spectroscopy, Photoluminescence (PL), and Near-Field Optical Microscopy (NSOM); (ii) Materials Growth and Deposition: Molecular Beam Epitaxy (MBE), Metal-Organic Chemical Vapor Deposition (MOCVD), Plasma-Enhanced

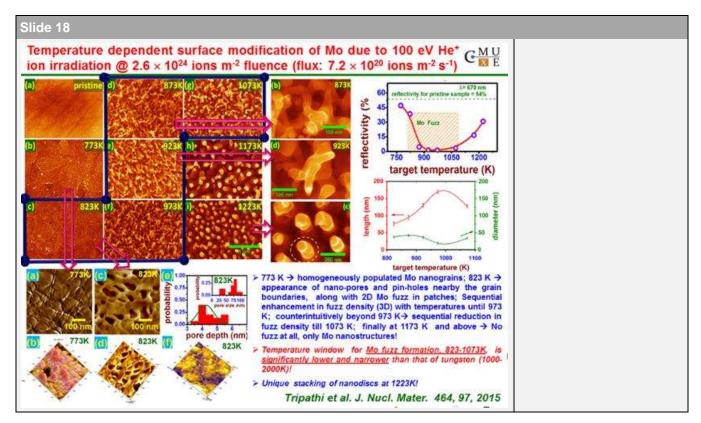
Slide 15	
	Chemical Vapor
	Deposition (PECVD),
	Halide Vapor-Phase
	Epitaxy (HVPE), Pulsed
	Laser Deposition (PLD),
	Atomic Layer Deposition
	(ALD), Reactive
	magnetron sputtering,
	Electron Beam
	Evaporation, Thermal
	Evaporation, and Sputter
	Deposition;
	(iii) Nanoelectronics and
	Microelectronics:
	Molecular Electronics,
	Nanowire Electronics,
	Carbon Nanotube
	Electronics, Silicon
	Microelectronics,
	Compound
	Semiconductor Devices,
	Wide Bandgap
	Semiconductor Devices,
	Thermoelectric Energy
	Conversion, and
	Photovoltaic Energy
	Conversion;
	(iv) Nanofabrication:
	Optical
	Photolithography, Electron-Beam
	Lithography, Circuit Layout
	Workstation, Optical
	Mask Generation,
	Reactive Ion Etching
	(RIE), Inductively
	Coupled Plasma (ICP)
	etching, Focused Ion
	Beam Machining, Plasma
	Etching and Cleaning,
	Wet Chemical
	Processing, Thermal
	Oxidation and Diffusion,
	and Rapid Thermal
	Processing (RTP);
	(v) Electronic
	Characterization:
	Current-Voltage

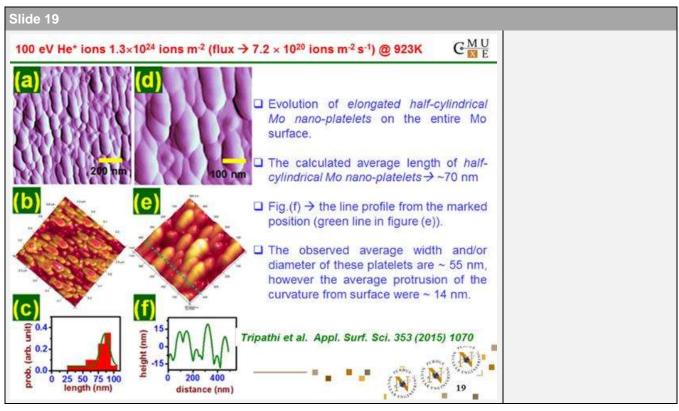
Slide 15	
	Metrology (μV to
	10 kV), Capacitance-
	Voltage Metrology,
	Admittance-Voltage
	Metrology, Admittance-
	Frequency Metrology,
	Deep Level Transient
	Spectroscopy (DLTS),
	Photoresponse
	Metrology, Hall Effect
	Metrology, Microwave
	Characterization (to over
	200 GHz) Variable
	Temperature
	Characterization (10 to
	650 K), and
	Ultra-Low-Temperature
	Electrical
	Characterization (using
	liquid helium).

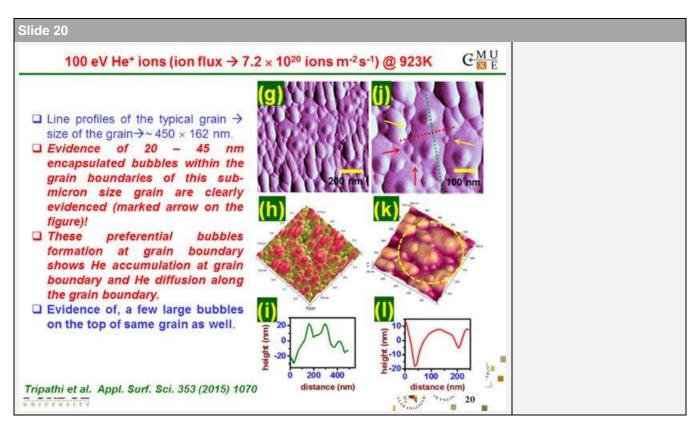
Slide 16 Ion Irradiations and advanced materials characterizations at CMU F CMUXE: Proposals / Projects (examples) ✓ Low energy high-flux ion induced modifications in high-Z refractory metals for nuclear fusion applications. ✓ Individual, Sequential, and Simultaneous dual ion beam irradiation induced surface modifications. ✓ Laser and ion beam exfoliations in 2D materials. √ Thermal desorption spectroscopy (TDS) studies. √ Nano structuring in novel 2D materials using pulsed laser deposition (PLD). ✓ In-situ low-energy irradiations (in a temperature range of LN2-1100C). ✓ Transient thermal heat loading (1.5 MJ m⁻²) on high-Z refractory metals for nuclar fusion applications. ✓ Nanostructuring in semiconductors *via* ion beam irradiations for their various technological applications. ✓ Ion induced surface modifications in thin film and multilayers. ✓ Self ordered and self organized nano patterning using ion irradiation.

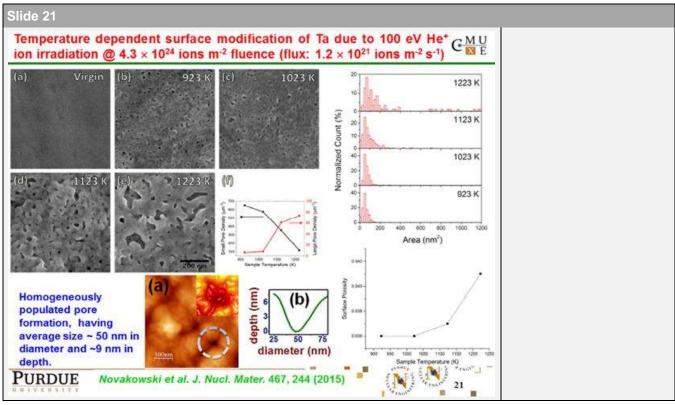
PURDUE

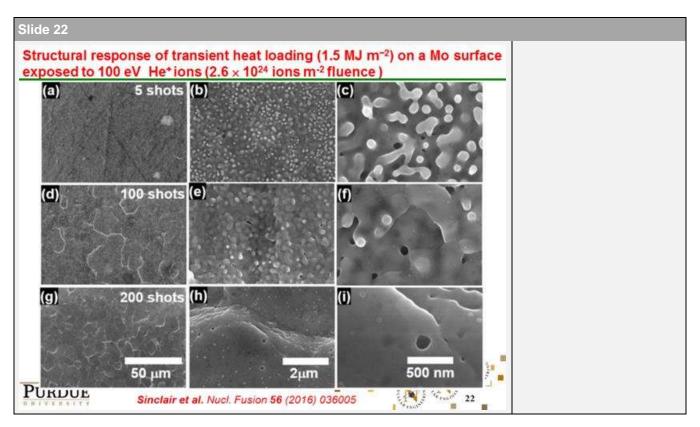
Purdue

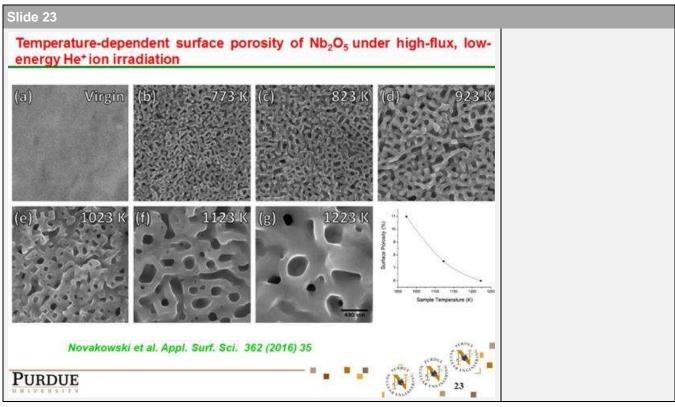




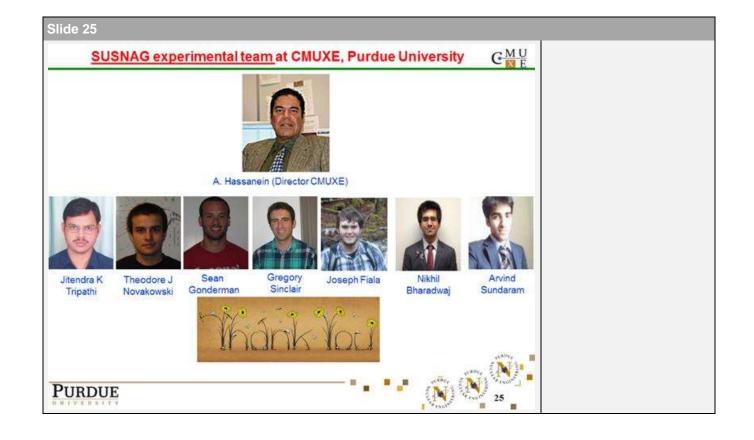






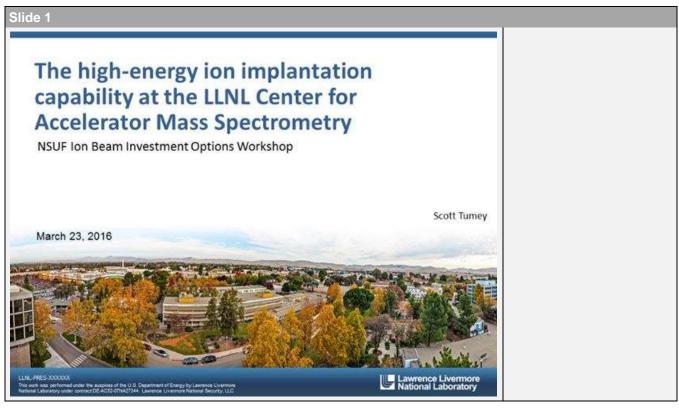


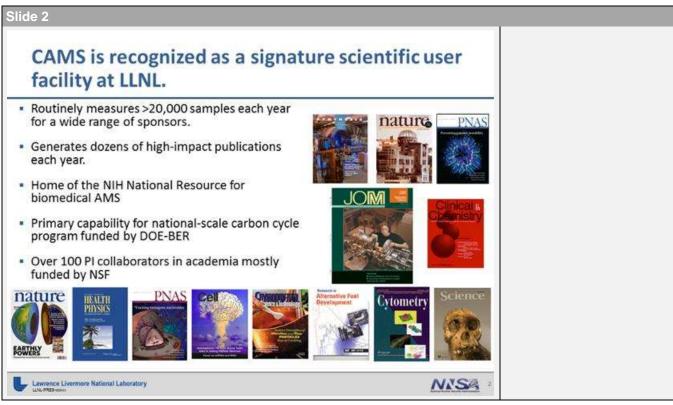
Slide 24 1. What materials can be CMU EME Conclusion handled? Actinides? □ Availability of low energy (70 -5 keV) high flux (up to 1.2 × 10²¹ ions m⁻² s⁻¹) helium, 2. We are NOT handling hydrogen, and deuterium ion irradiation facility. radioactive materials due ☐ Availability of in-situ low energy (300-1200 eV) high flux flux (up to 1.2 × 1021 ions m-2 to safety issue. s-1) helium, hydrogen, and deuterium ion irradiation facility. ☐ Availability of in-situ thin film & multilayer deposition, lon beam sputter cleaning, ion irradiation, XPS, AUGER, UPS, LISS and, EUPS facility. Availability of Individual, Sequential and Simultaneous dual ion beam irradiation ☐ E beam, RF sputtering and pulsed laser deposition (PLD) facility ☐ Availability of in-situ simultaneous "dual ion beam irradiation" and "transient heat loading" (using a ms laser). ☐ Possibility of the availability of 10k-100kV electron source gun. Availability of thermal desorption spectroscopy (TDS) facility. ☐ More information about the CMUXE are available at : https://engineering.purdue.edu/CMUXE/index.htmlhttps://atrnsuf.inl.gov ☐ Contacts: > Prof. Ahmed Hassanein (Director, CMUXE): hassanein@purdue.edu I > Dr. Jitendra K. Tripathi (Group leader of SUSNAG at CMUXE): jtripat@purdue.edu

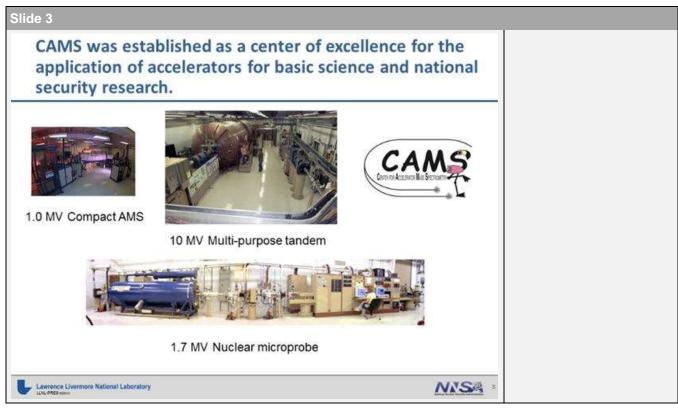


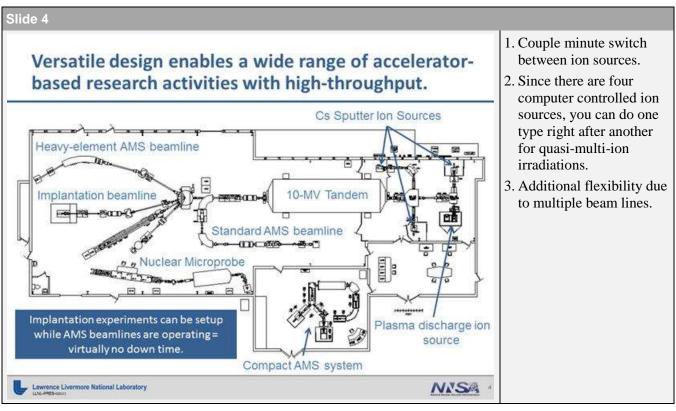
Presentation: High-energy Ion Implantation Capability at LLNL

Scott Tumey









Slide 5

Modular design of end-station allows for customization for each experiment.





- Wide temperature range (0-750 °C).
- Can conduct experiments with radioactive materials (e.g., HEU, Pu, etc).

Radioactive chamber



 Shielding enables experiments that produces prompt radiation.





Slide 6

Multiple ion sources can produce ions from nearly every element on the periodic table.

	H/D	He	Heavy ions (C, Fe, U)	Noble Gases
Typical energy	2-18 MeV	4-27 MeV	20-100 MeV	Under development
Maximum current	20-30 uA	5-10 uA	1-10 uA	
Applications	Isotope production, H injection	He injection	dpa	Fission product injection

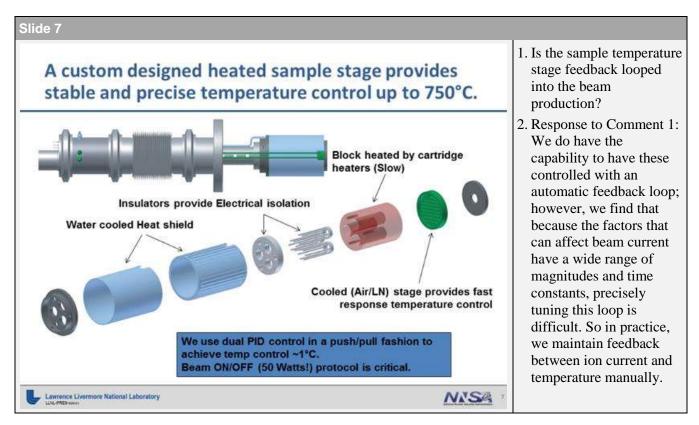


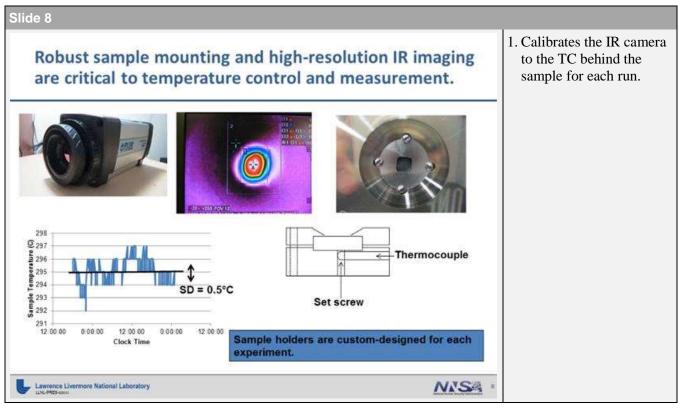


Lawrence Livermore National Laboratory

NISA .

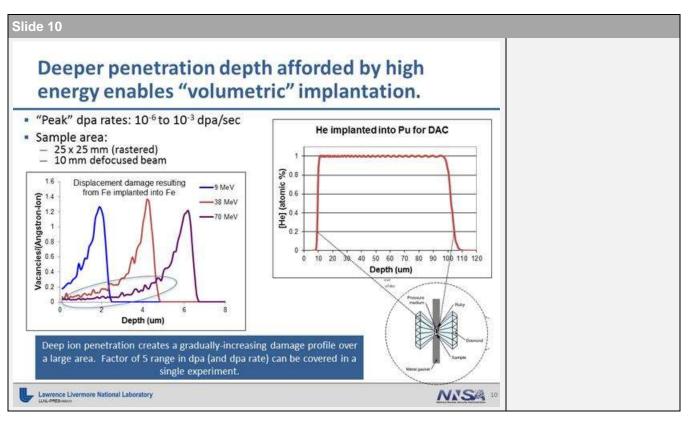
1. Can generate negative ions of some noble gases (work in progress).

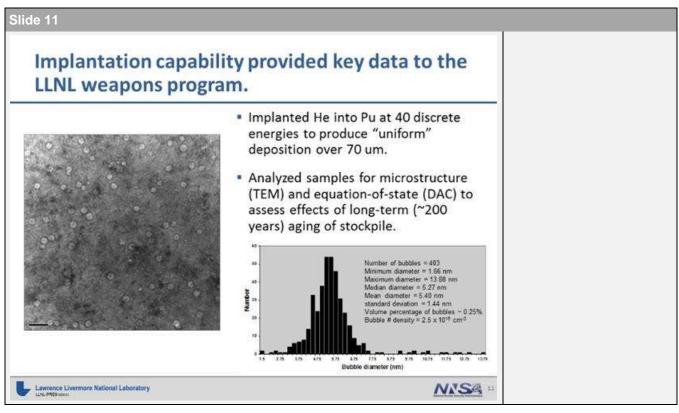


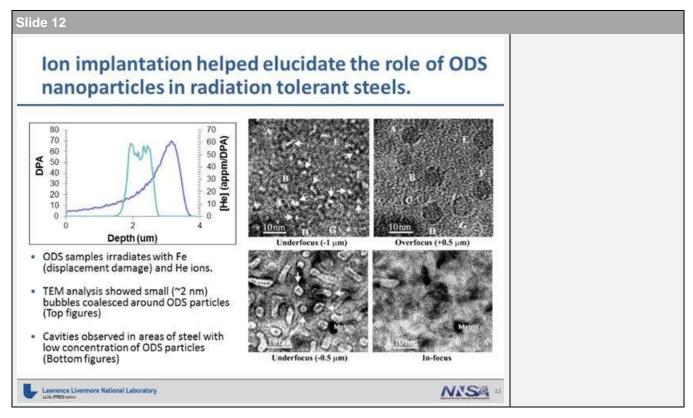


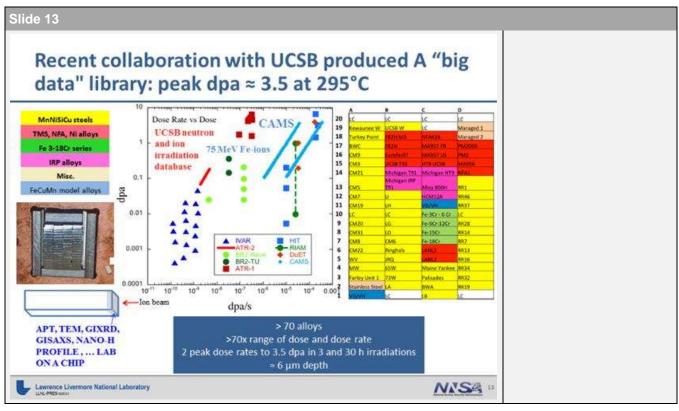
Slide 9 Absolute, two-dimensional beam dosimetry is challenging, but necessary when using a defocused beam. Custom-designed multi-pin Faraday cup enables reconstruction of spatial beam intensity. Rotating wire (BPM) provides diagnostic information in between Faraday cup measurements. Beam profile monitor trace 5.0 0.120 4.0 § 0.100 0.080 3.0 E 0.060 Signal (V) 2.0 FWHM ~ 8mm 1.0 0.000 0.0 -0.0180 -0.0160 -0.0170 -0 0150 Time (s) Lawrence Livermore National Laboratory

- 1. Do you keep a running tally of the beam profile, or is it an in-beam/out-of-beam measurement?
- 2. Regarding your comment about using the tails of the beam profile to achieve different damage levels, can you trust this method when the damage varies so steeply with position? Any beam "drift" will have a big impact on the actual damage to the sample.
- 3. Response to Comment 1: The Faraday cup measurements are periodic in beam measurements. We augment this with the BPM, which provides relative measurements constantly throughout the experiment.
- 4. Response to Comment 2: This is a very good point. Our beam stability is quite good, typically +/- 0.1 to 0.2 mm, and the drifts are captured by the BPM, which runs continuously throughout the experiment.









Slide 14

Accelerator is currently utilized at ~75% of available capacity.

Typical usage			
Maintenance	35 days		
Radiocarbon	150 days		
Be-10, CI-36, AI-26	50 days		
Actinides, I-129	25 days		
Implantation	15 days		
Unused	90 days		

 Modular design of accelerator system enables setup of ion beam experiments during other operations so nearly all unused days could be used for high-energy ion irradiation. 1. Approximately 90 days available for additional work. Setup can be performed when the system is being used for another irradiation.

Accelerator is supported by a large number of diverse sponsors, but there is sufficient capacity available to perform research relevant to NE.

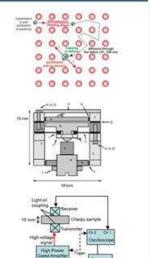




Slide 15

Upgrades to implantation end-station would greatly enhance the experimental capabilities available to NE.

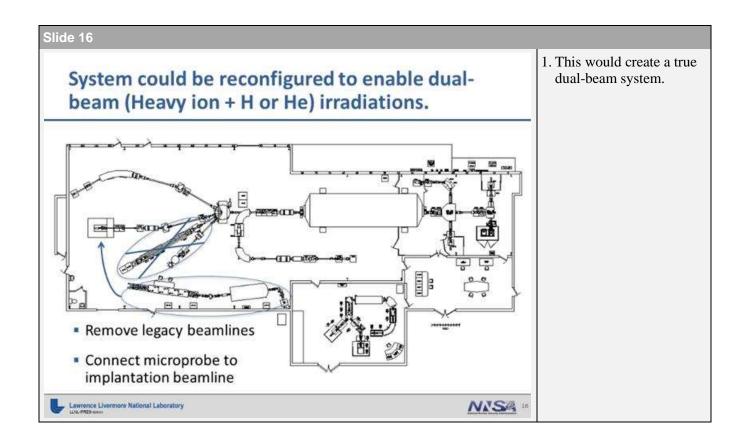
- Low-energy accelerator coupled with TEM (e.g., IVEM at ANL) is a powerful tool for in-situ characterization of microstructure evolution
- A similar approach built around the CAMS highenergy implantation beamline could allow for real-time studies of bulk property changes to materials under irradiation:
 - Non-equilibrium defect concentration via positron annihilation spectroscopy
 - Dimensional instability via capacitive plate dilatometry
 - Embrittlement and stress-corrosion cracking via nonlinear acoustic ultrasound



- 1. Proposed experiments bridge the gap between micro and macro structure properties.
- 2. Could measure both microstructure as well as physical properties.

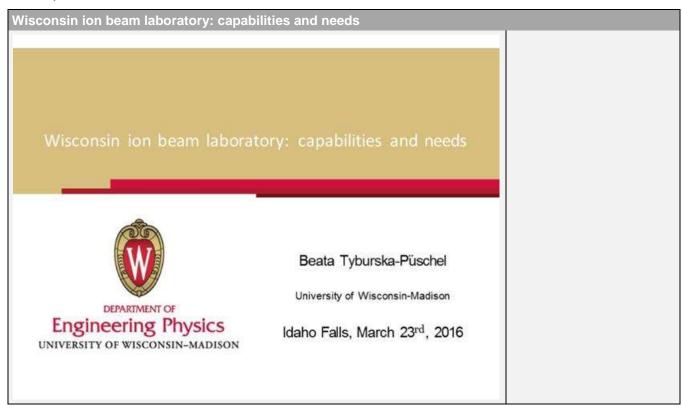
Lawrence Livermore National Laboratory





Presentation: Wisconsin IBL

Beata Tyburska-Pueschel



Introduction Introduction Introduction CLIM - Characterization Laboratory for Irradiated Materials In beam lab - ion-irradiation and IBA ATR-NSUF facility since 2011 PIE equipment Sample preparation Non- and radioactive samples: 10 mCi storage, 100 mR/hr unshielded on contact, no transuranic products

Ion-irradiation

Ion-irradiation



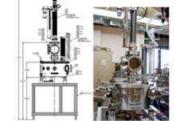
- 1.7MV tandem accelerator from NEC, 3 beamlines
- TORVIS and SNICS ion sources
- Almost all types of ions possible, no Noble gases except He, no low-current cathodes
- Max. area: 4 cm², various sample holders
- · Temperature controlled by thermocouples and IR camera
- · Beam spot observation and recording by a digital camera

3 of 13

New irradiation chamber

New irradiation chamber

- · Remote four jaws Ti slits
- · Chamber with a pre-chamber
- Sample goniometer
- In-situ RBS, NRA, PIXE
- Digital and IR camera



Irradiation parameters

External heating: $-150^{\circ} \text{ C} - 800^{\circ} \text{ C}$, 900° C flash Proton flux range: $1 \times 10^{11} - 2 \times 10^{15} \text{ p/(cm}^2)$ lon flux range: $4 \times 10^{10} - 6 \times 10^{14} \text{ ion/(cm}^2)$

4 of 13

1. Can change samples without breaking vacuum.

1. Commissioning a new sample chamber in April.

Sample goniometer

Sample goniometer

- Motorized 2-axis MultiCentre manipulator
- 1" diameter puck sample holder
- 6 pin type K thermocouple feedthrough
- Sample biasing/current measurement
- Tantalum wire heater element on a boron nitride mandrel for heating up 900° C (flash heating) and 800° C (radiative heating)
- LN2 sample cooling facility to −150° C



5 of 13

Other equipment

Other equipment

Radiation certified:

- Sample preparation equipment low speed saw, polisher, ion mill etc.
- Analysis techniques CLIM SEM with EDS and EBSD, TEM, XRDs
- MSC non dust producing equipment, e.g. Raman, AFM, etc.



- 1. What is the activity or dose rate level you can handle?
- 2. Answer: exposure 100 mRem/hr unshielded, on contact.

6 of 13

Projects

1. NSUF: 40-50% in 2016.

Projects

400 - 800 hours of irradiation per year, 10-20% NSUF

Federal grants

- Defects in off-stoichiometric UO₂
- Densification and thermal conductivity in irradiated UN and U₃Si₂
- · SiC: Ag diffusion, dose to amorphization, BSDs
- Neutron damaged simulation in steels
- · Hardness change with dpa in new Zr-containing ferritic steels

Current NSUF projects

- · Irradiation effects on properties of LWR concrete
- · Irradiation study of zirconium diboride

7 of 13



Lab needs

Lab needs

Lab needs:

- · Support to pay staff salary
- Upkeep of equipment
- Annual cost \$200k
- · Currently supported by NEUP/NSUF subject to fluctuation



8 of 13

Beamline 1 – *in-situ* irradiation and TEM

Beamline 1 -in-situ irradiation and TEM

Shift from subsequent to simultaneous

We have:

- . The 1.7 MV tandem accelerator
- JEOL 200CX TEM
- TEM technician for adjustments

We need:

- Space digitalize control room \$50k
- Adjust TEM \$20k
- Adjust the beamline
- Know-how ANL

9 of 13







- 1. Consider applying to the DOE-NE General Scientific Infrastructure Program for FY 2017 for this modification.
- 2. Would the in situ TEM be placed on one of the two unused beamlines?
- 3. What is the cost of microscope modifications?
- 4. Yes, it will be attached to Beamline 1, which at this moment still hosts an old irradiation chamber.
- 5. We estimate the total cost to be around \$130K.

Beamline 2 – in-situ corrosion, triple beam

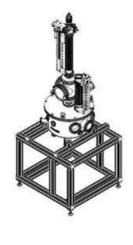
Beamline 2 -in-situ corrosion, triple beam

Triple beam (\$250k)

 Low-energy ion guns for simulations irradiation with e.g. He (bubble formation) and Ag (diffusion in SiC)

In-situ corrosion stage (\$50-100k)

- Study synergistic effects of irradiation and environment in FHR
- Development of a dedicated beamline for studying the coupling effect of irradiation and corrosion in HT/LP molten salts.



1. Consider applying to the DOE-NE Infrastructure grant program for these modifications.

10 of 13

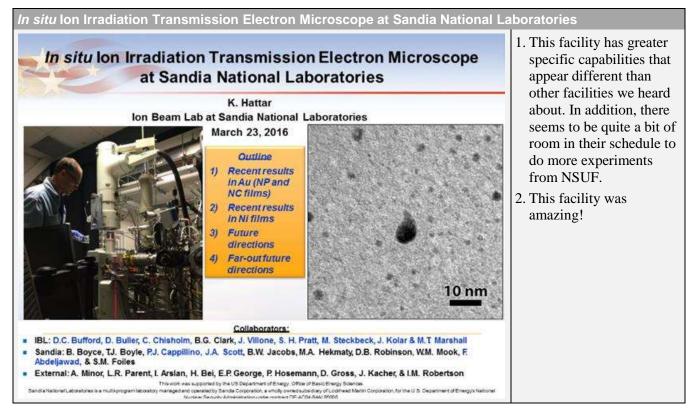
Criteria Criteria Facility Response or Programmatic/User Needs Ability of the facility to provide a variety of ion 1 MeV - 5.2 MeV, max. 8.5 MeV after repairs and upgrades. C2 irradiations (ion types, energies, multiple beams, IONS: H, D, He, sputtered ions; no Nobel gases. Single gun, triple beam is planned Ability of the facility to collect and analyze In-situ depth profiling and concentration analysis of implanted microstructural characterization data onsite and inspecies through ion beam analysis; surface chemistry monitoring situ. through PIXE About 20% of irradiation time goes to NSUF, 70% to federal NE support and activities (performed and C5 anticipated) at the facility including the volume of projects, and 10% to other projects. Recently won a NEUP infrasturcture grant (\$200k), total 4 NSUF project, currently 2 experiments that can be handled. ongoing, numerous NEUP, IRP, and NSF projects. Total irradiatio hours about 400-800/year, estimate for 2016 is 1200 h State license for storage and treatment of radioactive material. C7 Ability of the facility to handle radioactive materials in the beams and elsewhere onsite. No transuranic products. Storage limit 10 mCi. Max. exposure of 100mR/hr unshielded, on contact. Hot cell, sample storage, licenced equipment for sample prep and analysis. 11 of 13

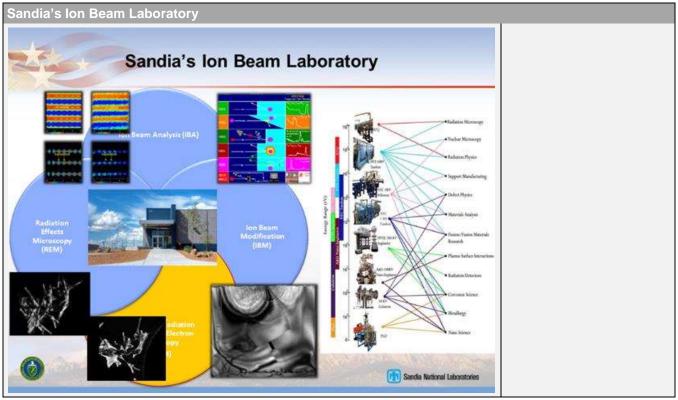


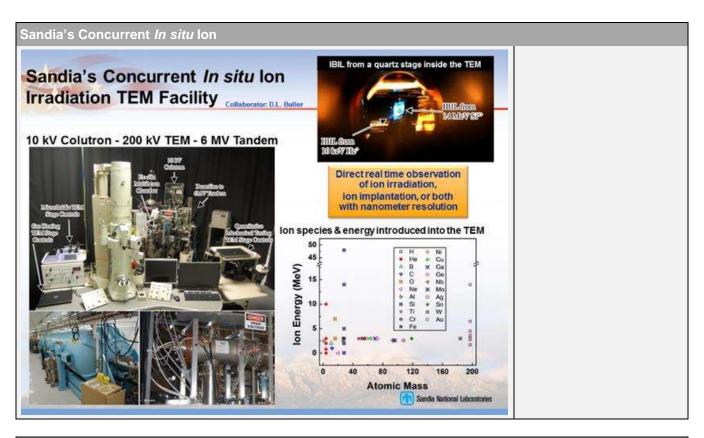


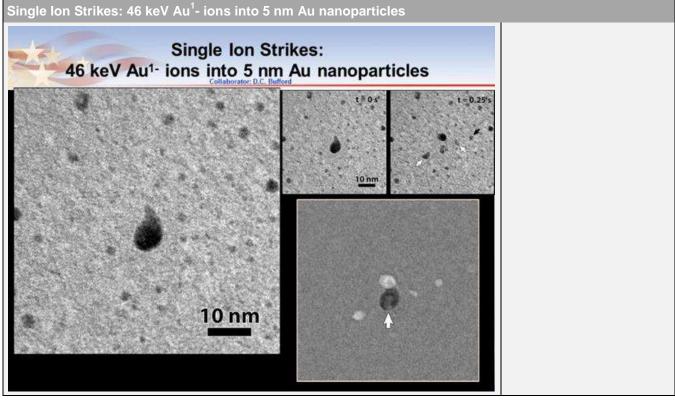
Presentation: In situ Ion Irradiation Transmission

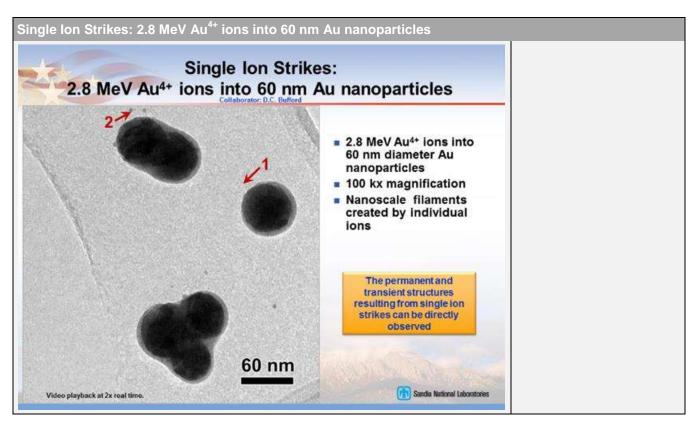
Khalid Hattar

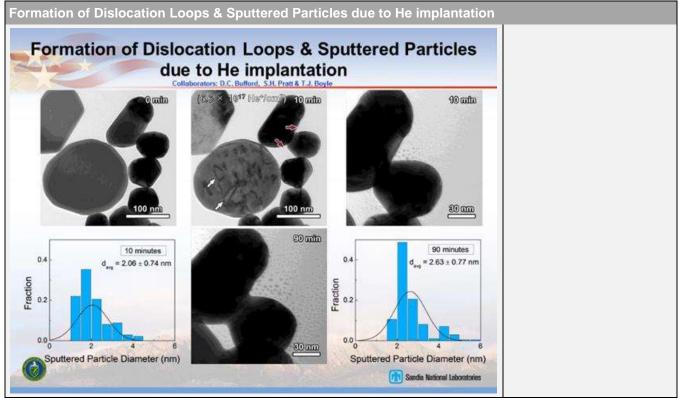


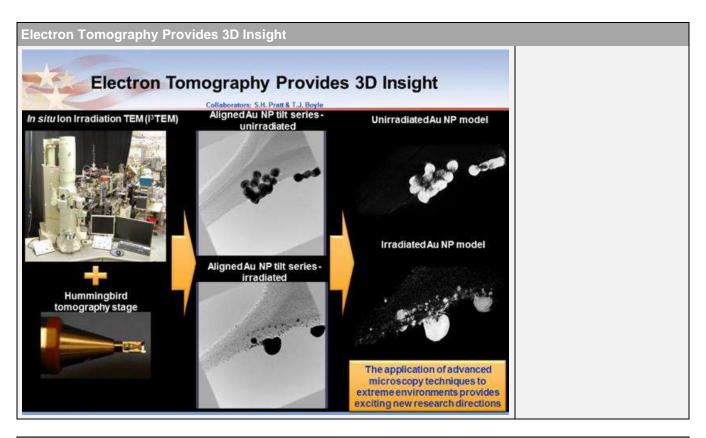


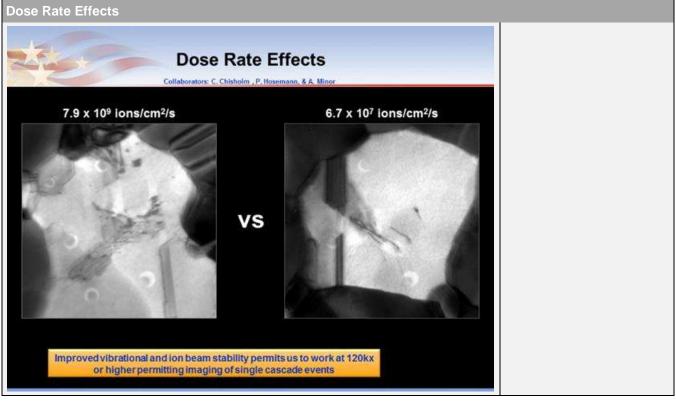


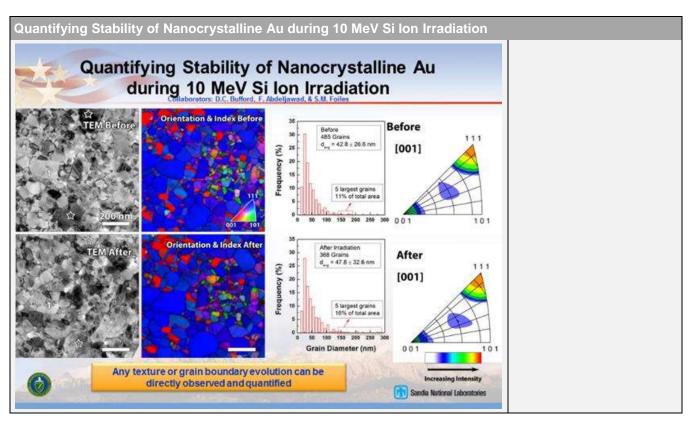


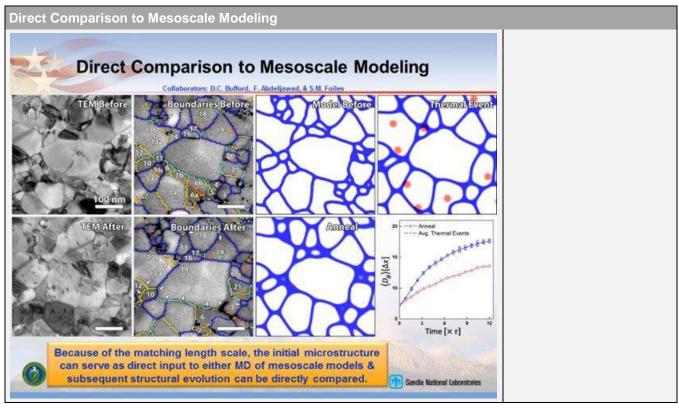


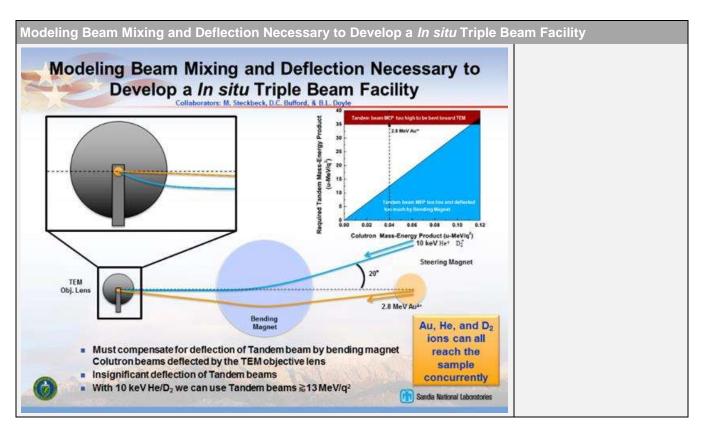


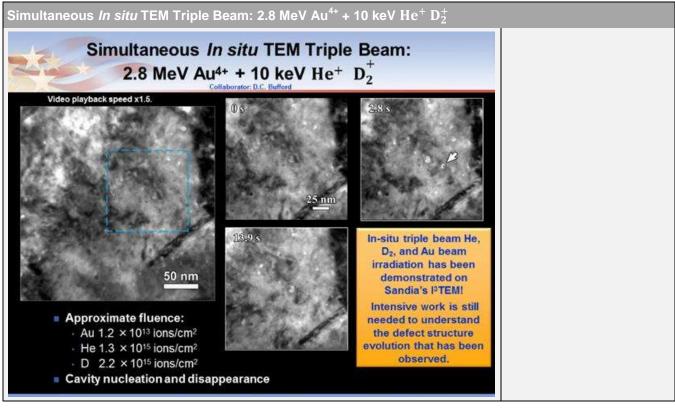


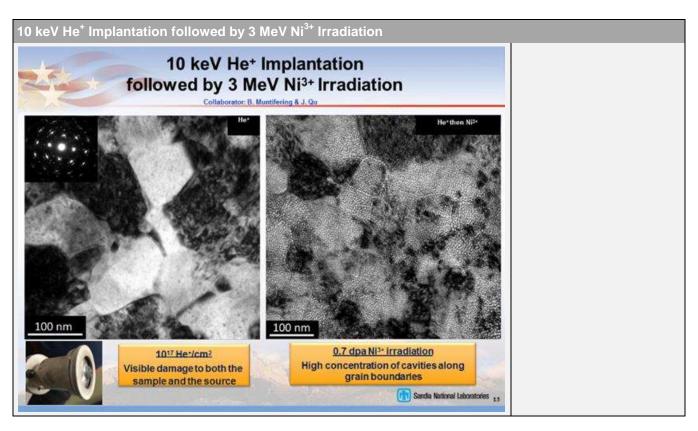


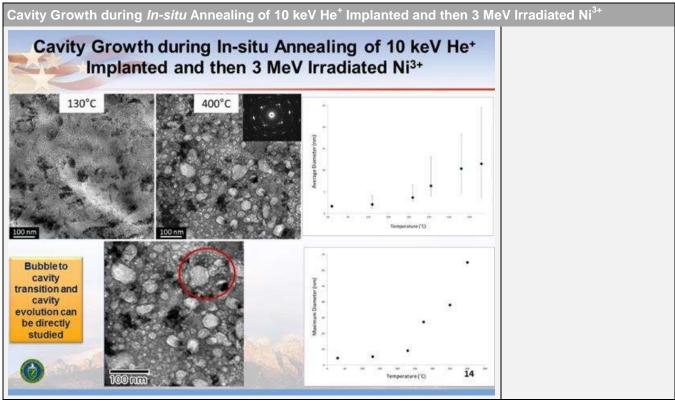


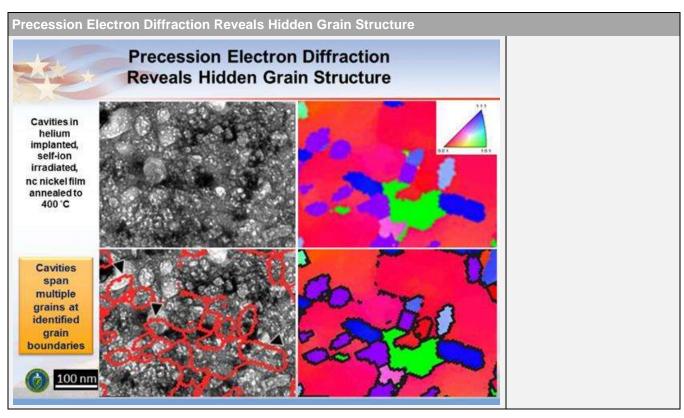


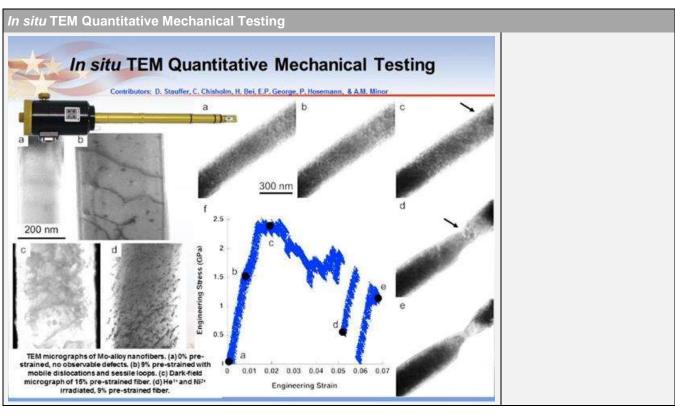


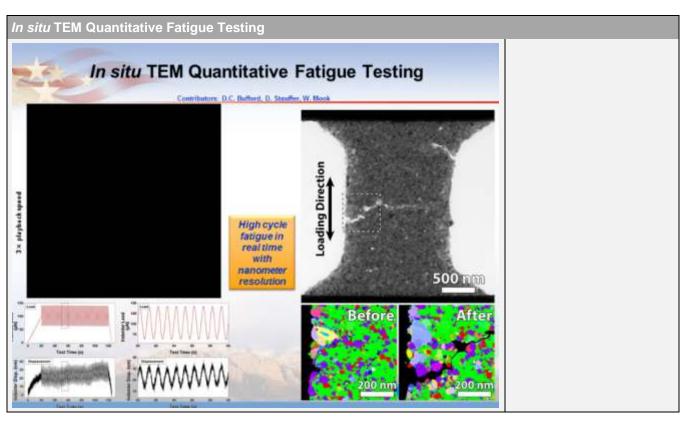




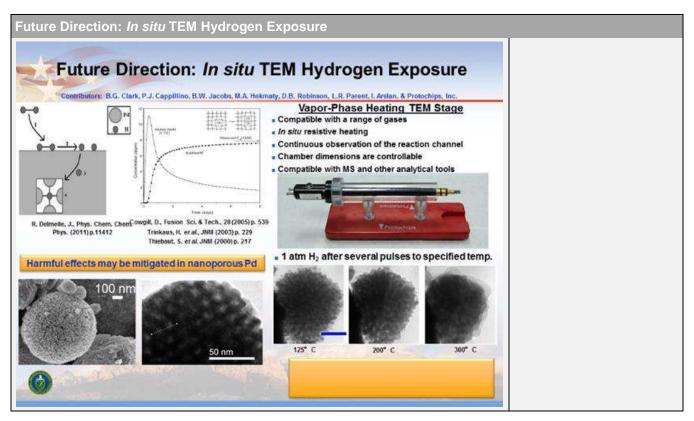


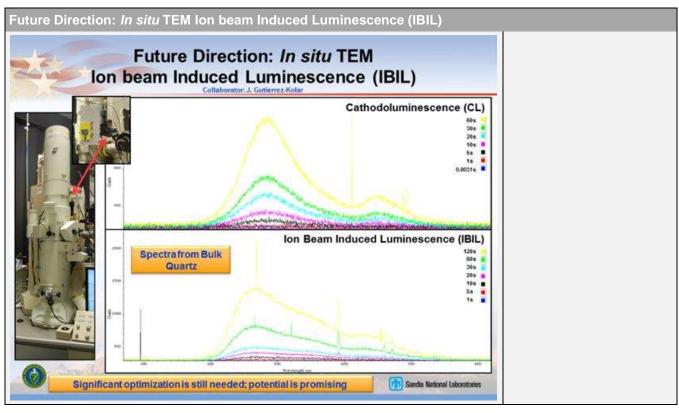


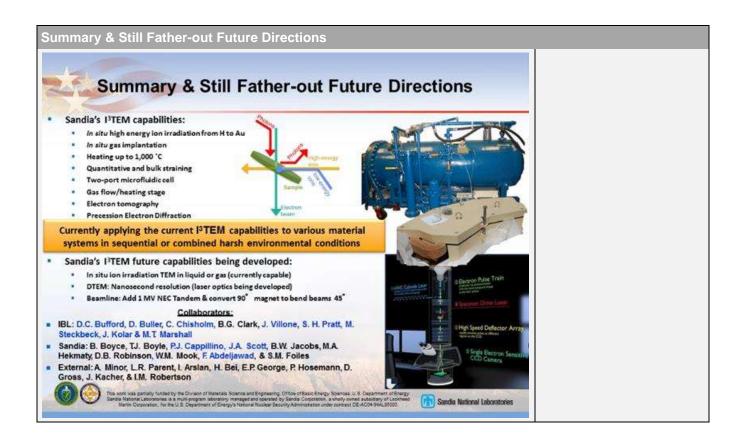












Presentation: Michigan IBL

Michigan Ion Beam Laboratory

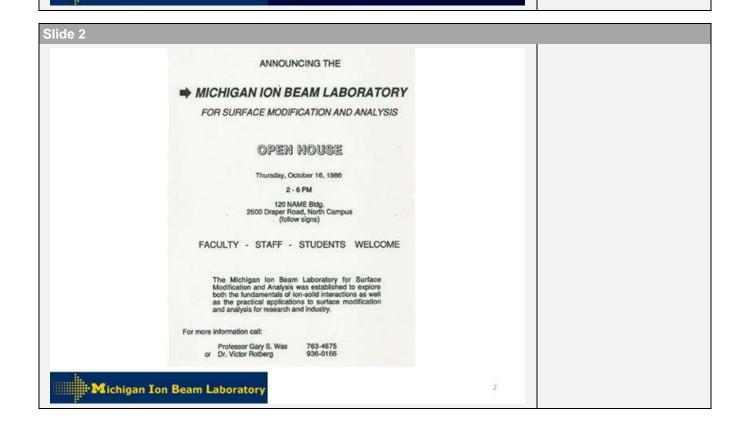
Gary Was

Ion Irradiation Capabilities and Needs at the Michigan Ion Beam Laboratory – a NSUF Partner Facility – Nuclear Engineering and Radiological Sciences University of Michigan

Ion Irradiation Capabilities and Needs at the Michigan Ion Beam Laboratory a NSUF Partner Facility

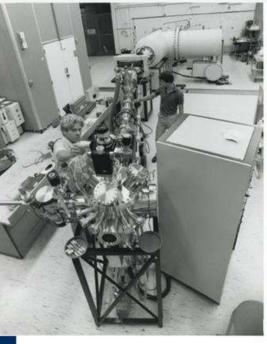
Nuclear Engineering and Radiological Sciences
University of Michigan

Gary S. Was
March 23, 2016



Slide 3

MIBL October, 1986





Slide 4

ATR-NSUF Partnership

Date: Thu, 5 Feb 2009 09:52:31 -0700

Dear Dr. Was:

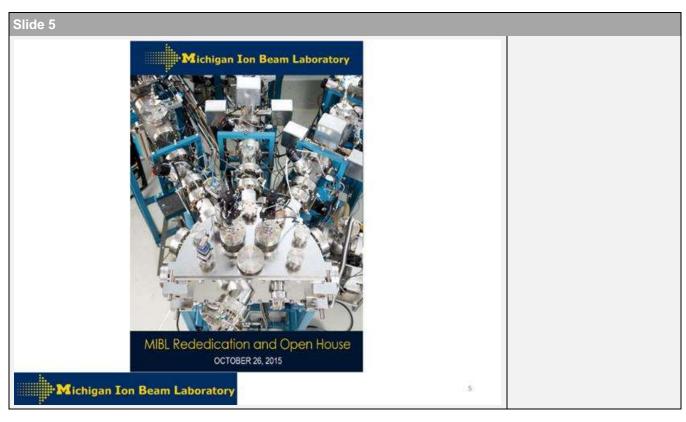
Congratulations, your facility has been selected to join the ATR NSUF as a research partner. Attached below is the formal selection letter.

Welcome to the NSUF team. If you have any questions about your selection, please don't hesitate to contact me.

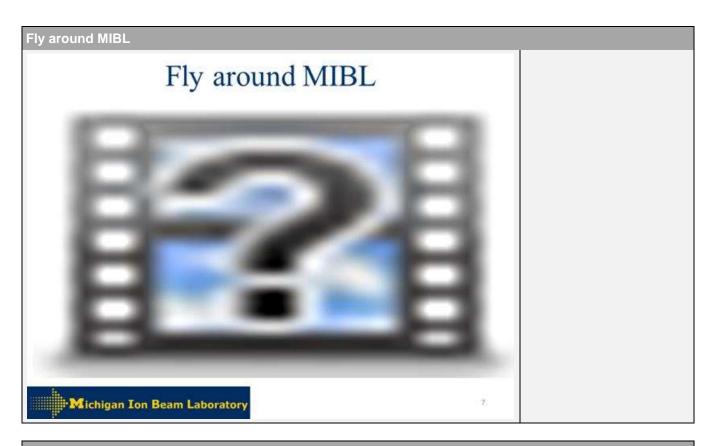
Todd R. Allen Scientific Director ATR National Scientific User Facility



1





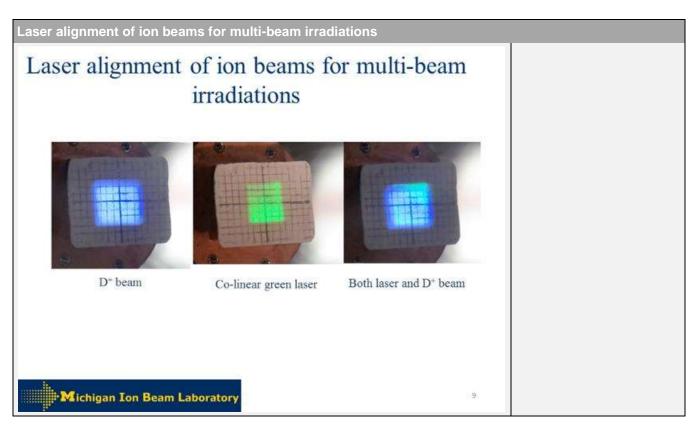


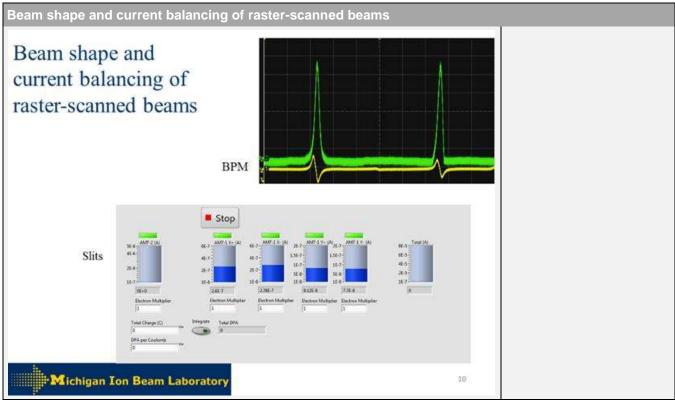
Ion Irradiation Capabilities at MIBL

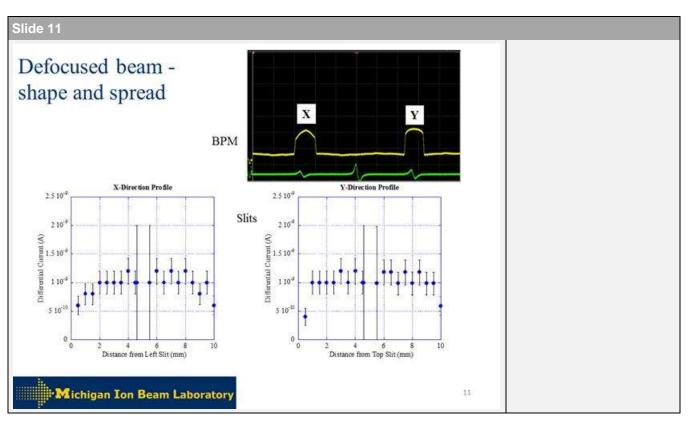
Ion Irradiation Capabilities at MIBL

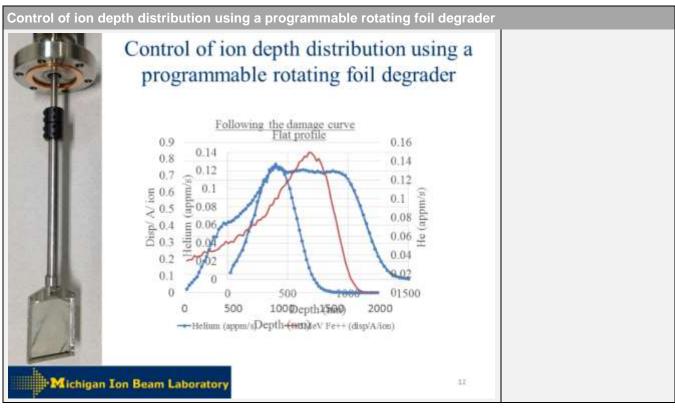
- · Single Ion Irradiations
 - Proton irradiation to moderate dose
 - Self-ion irradiation to high dose
 - In-situ corrosion
- · Dual Beam Irradiations
- · Triple Beam Irradiations
- Dual Beam In-situ TEM (in progress)
- · Ion Beam Analysis
 - Rutherford backscattering spectroscopy (RBS)
 - Nuclear Reaction Analysis (NRA)
 - Particle Induced X-ray Emission (PIXE)
 - Elastic Recoil Detection (ERD)
 - Ion channeling

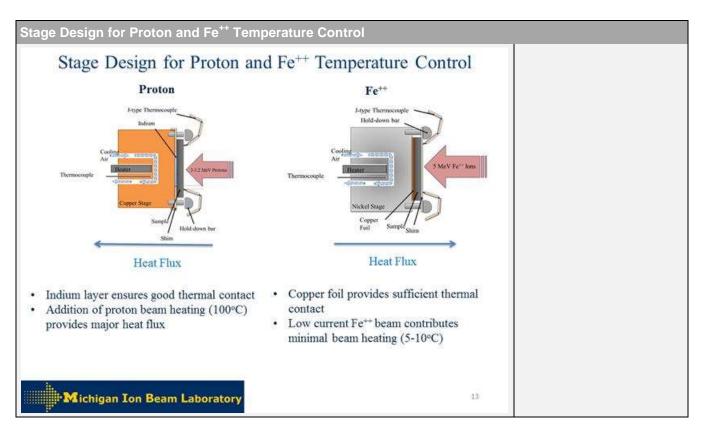


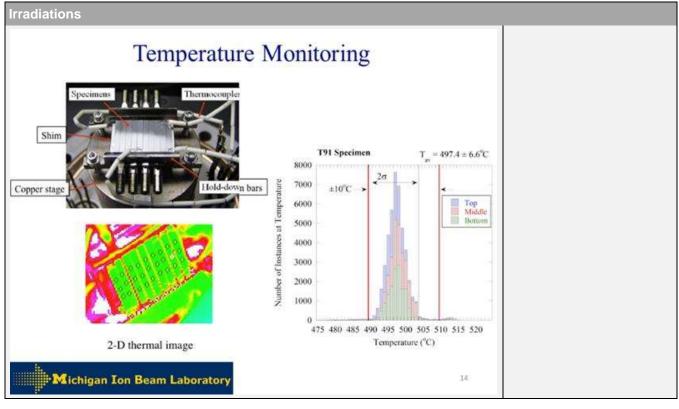


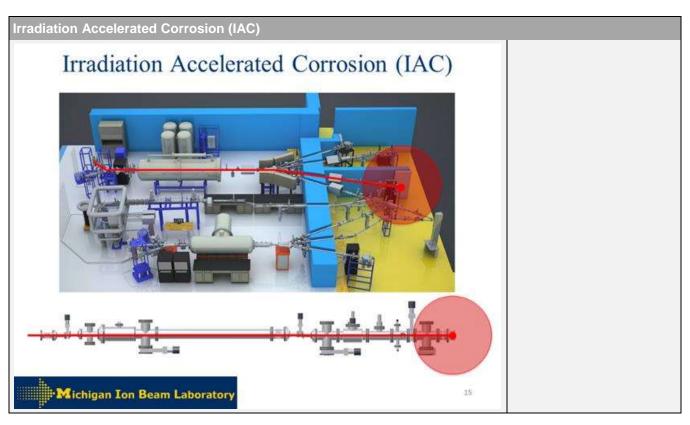


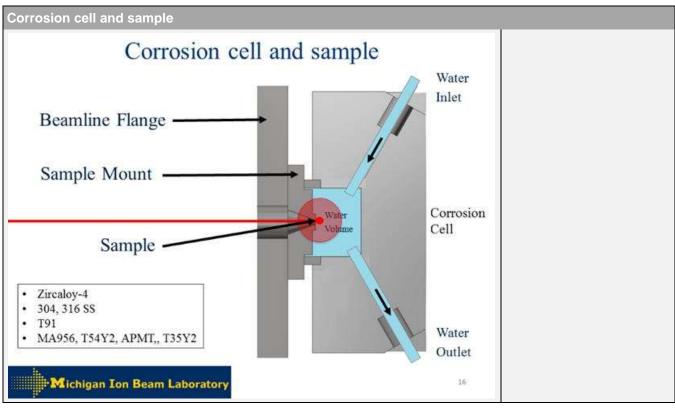


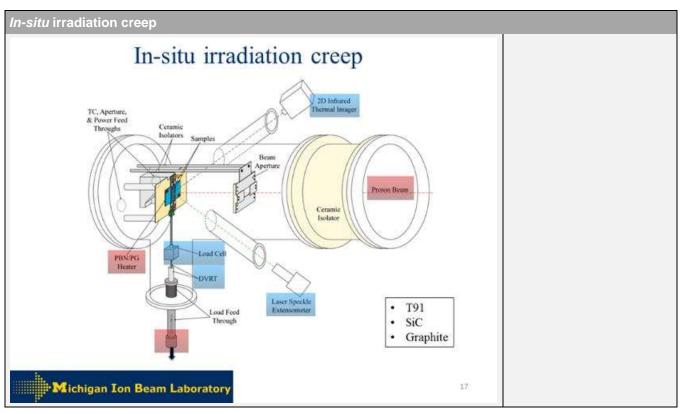


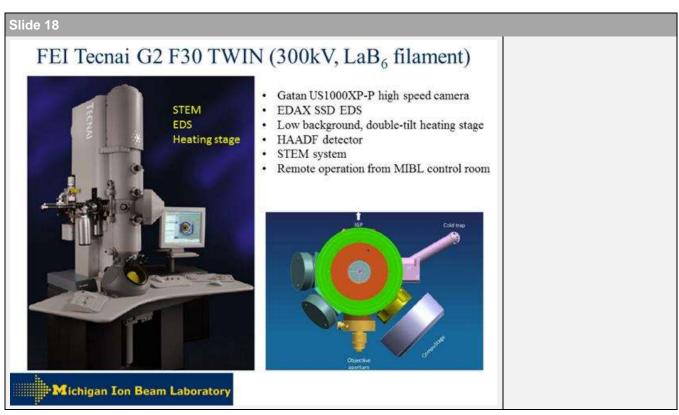


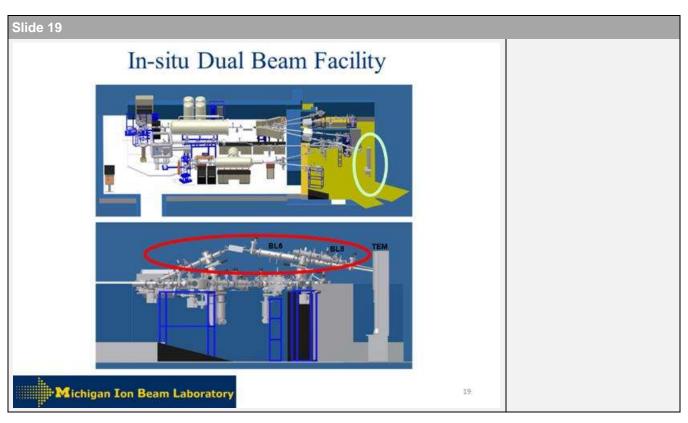


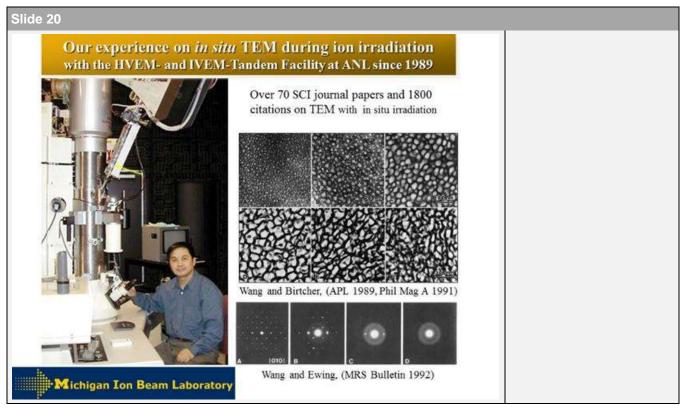






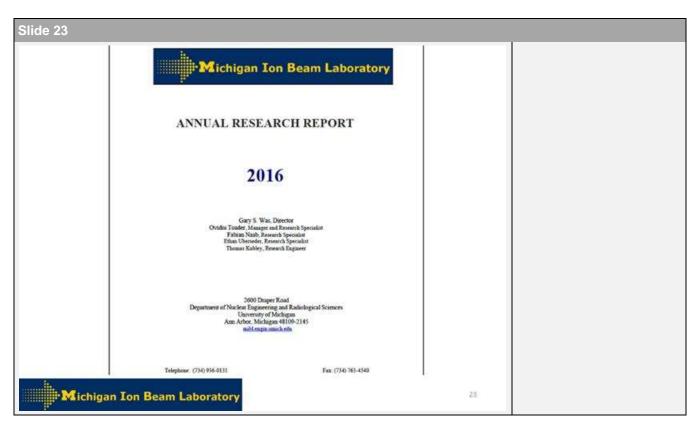


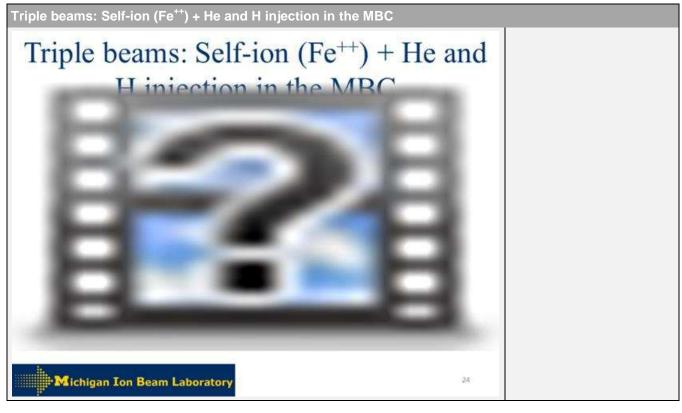












Addressing a wide range of dpa, He, H production

Damage rate, He/dpa and H/dpa for various reactor types

Reactor type	Fast (F-M)	LWR (stainless)	CANDU (Ni-base)	Fusion (F-M)	SNS (F-M)
Dose rate (dpa/s)	1×10 ⁻⁶	5×10 ⁻⁸	2×10 ⁻⁷	10"-10"	10'8-10"
He/dpa (appm/dpa)	0.2	2-5	300	~10	~100
H/dpa (appm/dpa)	- 2	12	60	70	1700

Achievable damage rate, He/dpa and H/dpa in MIBL

Ion	400 KV implanter	1.7 MV Tandem	3.0 MV Tandem
Fe**	-	10 ⁻³ -10 ⁻³ dpa/s	10°-10° dpa/s
He2	0.1 - 10° appm/dpa	0.1 - 10° appm/dpa	0.1-10° appm/dpa
H,	0.1-10° appm/dpa	0.1-10° appm/dpa	0.1-10° appm/dpa



25

Slide 26

Use of Ion Irradiation to Study Nuclear Fuel

- Xe (up to 1 μ A of 1.6 MeV Xe) and Kr (up to 1.5 μ A of 1.2 MeV) ion irradiation to study fission gas effect.
- He ion irradiation to study α particle irradiation effect.
- In-situ Kr/Xe ion irradiation in TEM to study microstructural evolution with or without gas effect depending on ion energy and sample thickness.
- Heavy ion irradiation with Zr or Mo ions (both with high fission yield) to study interface stability under irradiation.
- Ion irradiation to study fuel-matrix-interaction (FMI) or fuel-cladding-chemical-interaction (FCCI) behavior.



26

Experience and capability

In 2013 > 6600 beam hr logged on irradiation effects studies in MIBL (~200 irradiations) for 130 researchers and 52 projects. In last five years:

- Labs: INL, LANL, ORNL, PNNL, Bettis, U.S. Army Research Lab
- Universities: Boise State, Wisc., Connecticut, Texas A&M, Windsor, Illinois, Va. Tech, Virginia, Cornell, Colorado School of Mines, Southern California, Wayne State, Ohio State, Buffalo, Notre Dame, San Antonio, Tennessee, Alabama A&M, Duke Univ., Brown Univ., UCLA, Rutgers, Delaware, Pennsylvania, McMaster
- International:

France - Areva, CEA, CNRS, U. de Toulouse, Ecole Nat' 1 Sup. Paris

U.K. - U. Manchester, Oxford

China - IMR, SNPRI, SNERDI, Northeastern U., SJTU, U. Electr. Sci. and Technol.

Canada - AECL

Japan - INSS (Japan)

Germany - Helmholtz Center

Poland - Institute of Physics

Chech Republic - NRI

Korea - KAERI

Pakistan - Lahore College for Women, NILOP, Pakistan Inst. of Engin & Appl Sci



27

Slide 28

Current UM-based Projects at MIBL

- · EPRI ARRM program on IASCC
- · EPRI 718 program on IASCC of 718 as a function of microstructure
- DOE-BES program on mechanism of IASCC
- DOE/EPRI LWRS program on IASCC mechanism and modeling
- · NEUP program on IASCC mitigation
- MAI/EdF program on IAC
- · 5 NEUP programs on Accident Tolerant Fuel Development
- NEUP program on accelerated irradiations for high dose microstructures
- · NEUP program on radiation induced segregation
- CASL project on oxidation and hydrogen uptake in Zr under irradiation
- · DOE-IRP on High Fidelity Ion Irradiation to Emulate Reactor Irradiation
- · TerraPower project on core materials development



28

Accomplishments



Journal of Nuclear Materials 300 (2002) 198-216



Emulation of neutron irradiation effects with protons: validation of principle

G.S. Was a*, J.T. Busby a, T. Allen b, E.A. Kenik c, A. Jenssen d, S.M. Bruemmer c, J. Gan c, A.D. Edwards c, P.M. Scott f, P.L. Andresen g





Available online at www.sciencedirect.com

ScienceDirect

Scripta Materialia 88 (2014) 33-36



Emulation of reactor irradiation damage using ion beams

G.S. Was, ^{a, a} Z. Jiao, ^a E. Getto, ^a K. Sun, ^c A.M. Monterrosa, ^a S.A. Maloy, ^b O. Anderoglu, ^b B.H. Sencer ^c and M. Hackett ^d



29

Slide 30

Professional Staff at MIBL



Ovidiu Toader, PhD; Lab Manager



Fabian Naab, PhD; Research Specialist



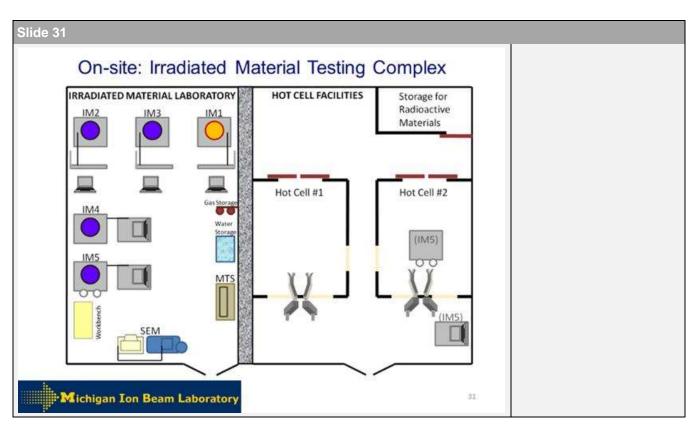
Ethan Uberseder, PhD; Research Specialist

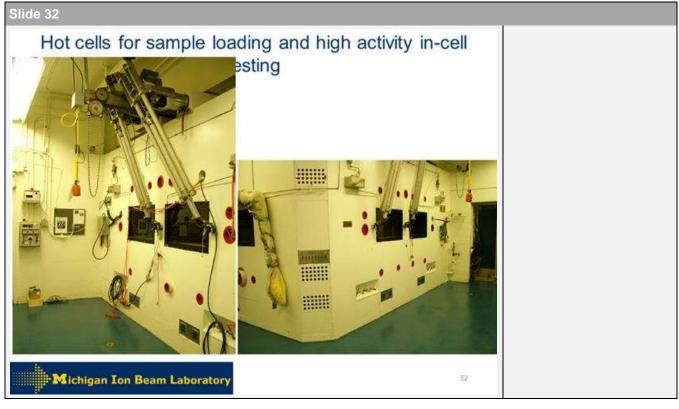


Thomas Kubley, MS; Accelerator Engineer

2





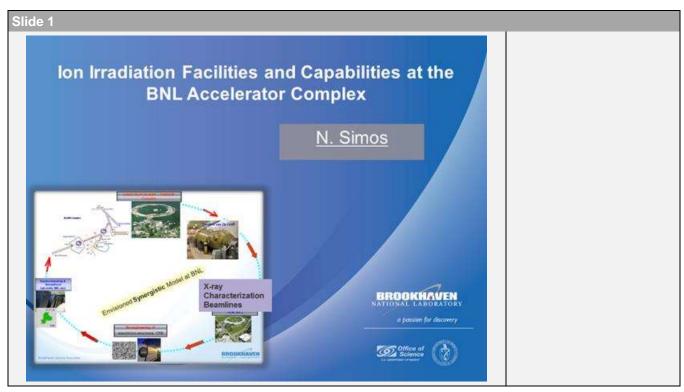








Presentation: Accelerator Based Facility for Materials Irradiation Testing Nick Simos





Slide 3 **BNL Irradiation and Characterization Facilities Synergy** BLIP (Brookhaven Linear Isotope Producer): Irradiation studies using (a) high energy protons (66 MeV to 200 MeV) and (b) spallation neutrons from 118 MeV protons on target. Materials for fusion and fission reactors as well as high power accelerators (LHC, LBNF, FRIB, etc.) NSRL - 2 GeV protons + High Energy lons Tandem Van de Graaff:

Irradiation facility with 28 MeV protons or ions from an ion array up to 197Au

Isotope Extraction-Processing Facility:

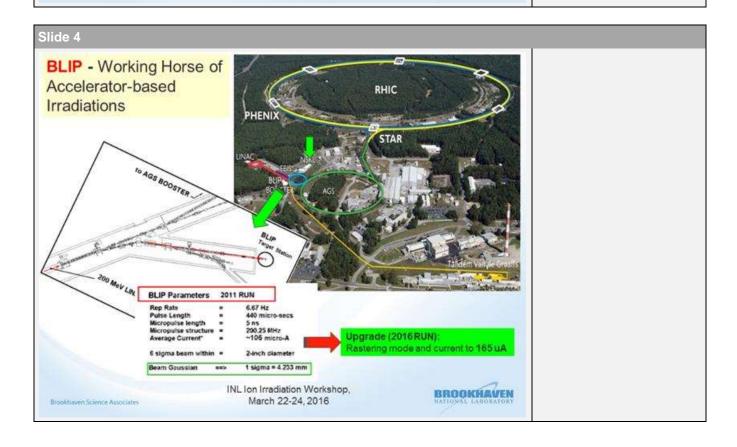
An experimental area in the facility hot cells for complete macroscopic analysis of irradiated samples

NSLS II - X-ray diffraction

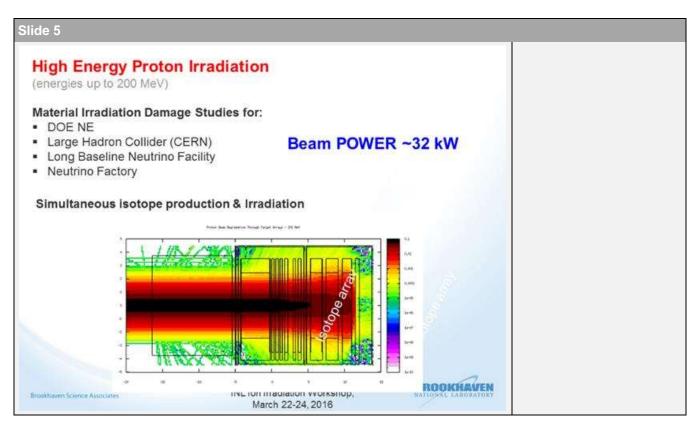
Center for Functional Nanomaterials (CFN) - Characterization

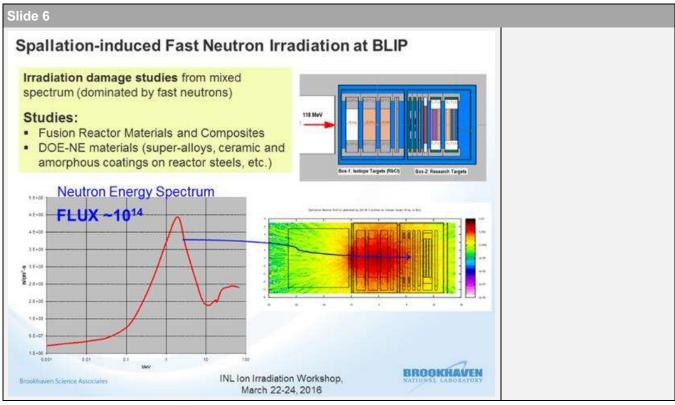
INL Ion Irradiation Workshop, March 22-24, 2016

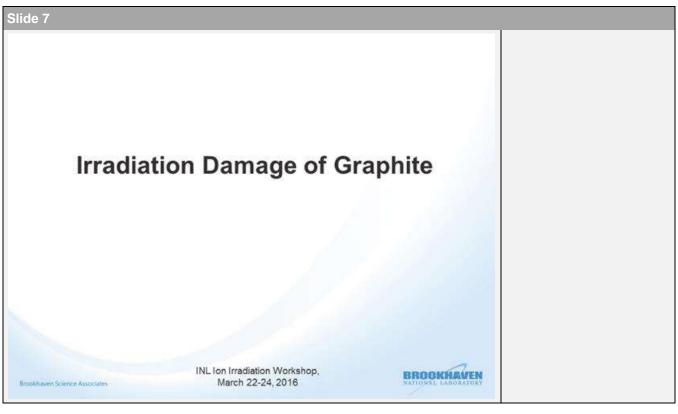
1. Working on getting CFN to handle radioactive materials.

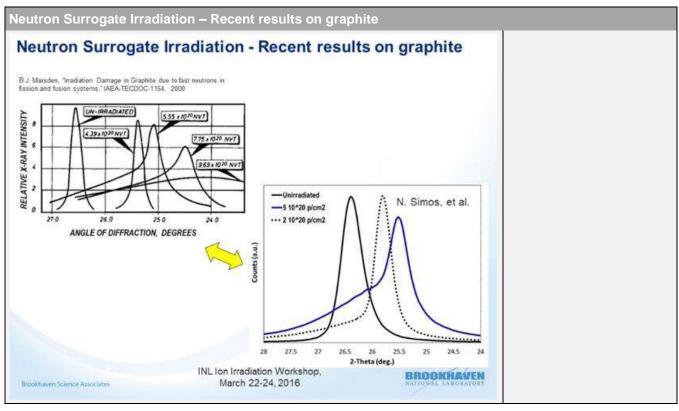


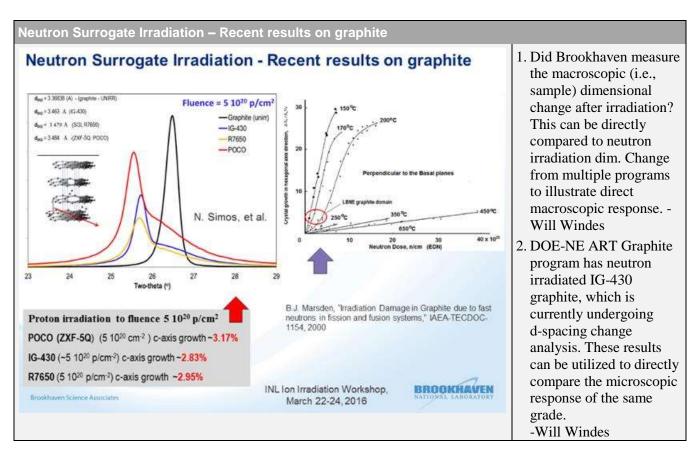
BROOKHAVEN

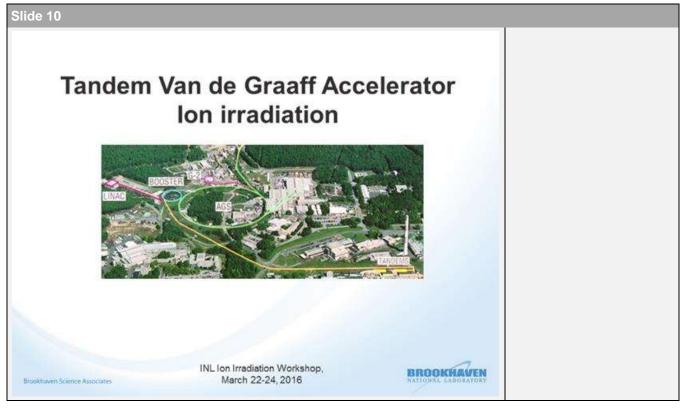




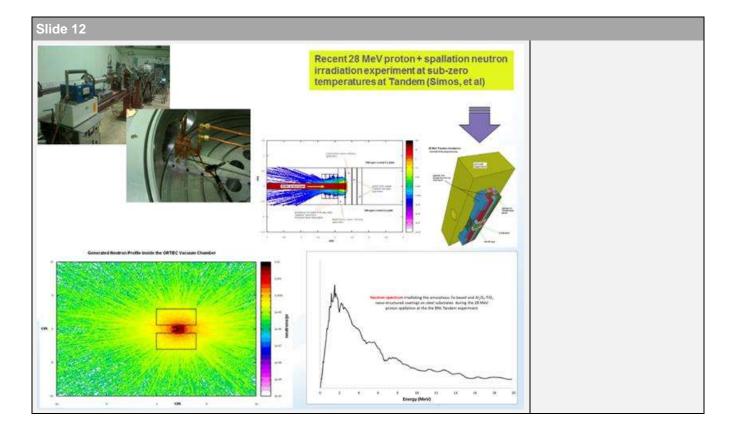


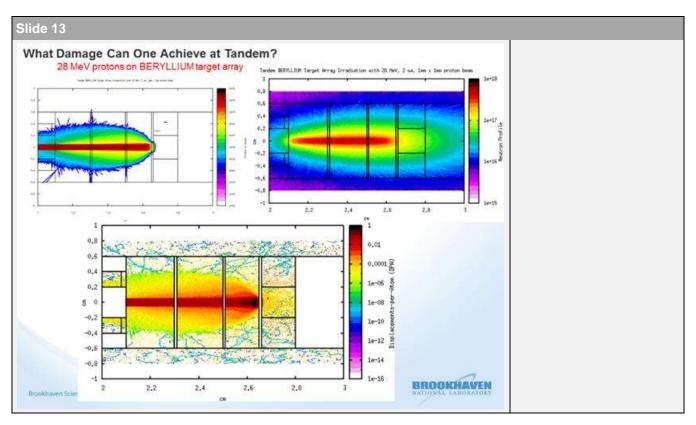


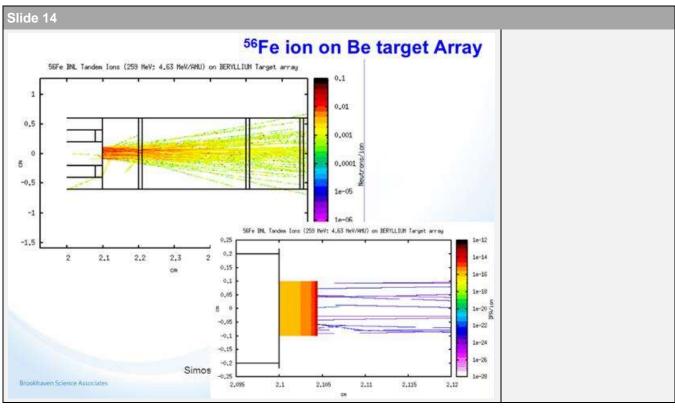




Slide 11 1. How hot are typical 28 MeV Proton & Heavy ion irradiation at Tandem - 2 uA current samples after a high-dose irradiation study? Surface LET Range Surface LET Mass Tandem van De Graff MeV MeV MeV AMU AMU MeV ng/cm² 'H 1,0079 28.75 28.52 0.0153 4550 2610 11.0093 85.5 206.13 1.46 180.43 12.0000 99.6 115.82 15.999 128 88.9 18.995 142 3.51 118.88 2.45 23.9927 55.13 161 84.16 28,0855 187 7.81 77.16 5,42 50,66 212 42.71 6.06 11.5 64.41 7.93 39.975 15.8 47.9479 232 4.84 47.8 13.4 32.36 19,6 51.9403 245 4.72 45.86 15.3 31.06 55.9349 44.24 30,09 57,935 4.66 44.56 19.1 30,47 270 27.9 62,929 4.40 42.06 28.79 71.9221 273 3.80 37.94 26.25 24.4 3.55 37,50 26,11 41.3 28,0 92,9060 25.4 106.9051 313 32.48 22.89 126.9045 322 2.54 32.54 45,0 23.17 29.21 56.2 INL Ion Irradiation Workshop N March 22-24, 2016



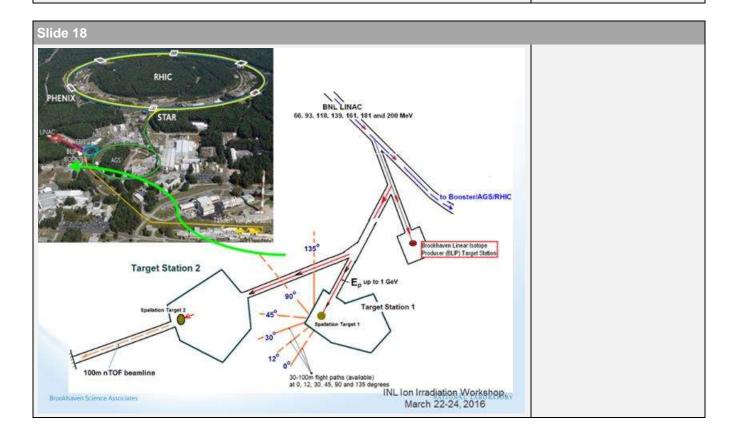






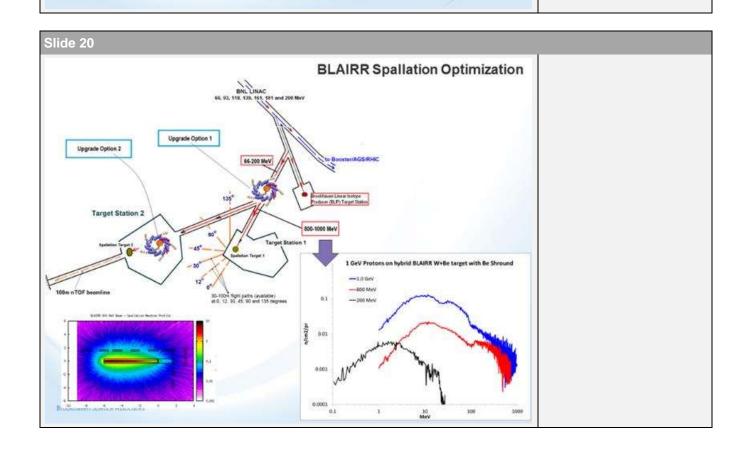


Looking ahead BLAIRR A Dedicated, Accelerator-driven Irradiation Facility offering DOE-NE a complementary approach to the research reactors (ATR, etc.) BLAIRR aims to capitalize on the existing/dormant infrastructure of the old REF/NBTF complex and update it into an irradiation and test facility that can fill the gap in the DOE complex INL Ion Irradiation Workshop, March 22-24, 2016



Slide 19 Aim: Capitalize on Complex Unique Features: Multitude of energies the Linac can provide FAST neutron damage studies of materials for Polarized H fast neutron and fusion reactors Beam current (165 µA → 2 x in planned update Proton irradiation damage of materials for accelerator initiatives as a function of energy Heavy ions from Tandem down same beamline Validating experiments of neutron flux/reaction rates for accelerator-driven systems Availability of infrastructure (currently dormant) Blanket, moderator, reflector concept Neutron time-of-flight path lengths of 30-100 validation/optimization meters at 0, 12, 30, 45, 90 and 135° Nuclear cross-section data Single micro-pulse selection (<1 ns) with period Neutron detector studies as low as 400ns Expansion of the range of isotope generation augmenting BLIP capabilities Neutron scattering potential Neutron time of flight (nTOF) and nuclear physics experiments INL Ion Irradiation Workshop, BROOKHAVEN March 22-24, 2016

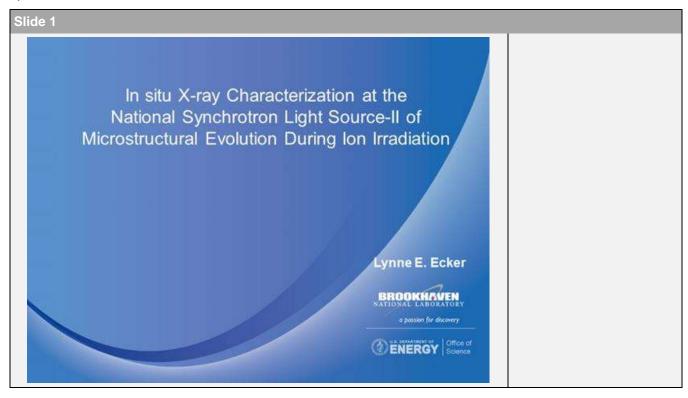
Brookhaven Science Associates

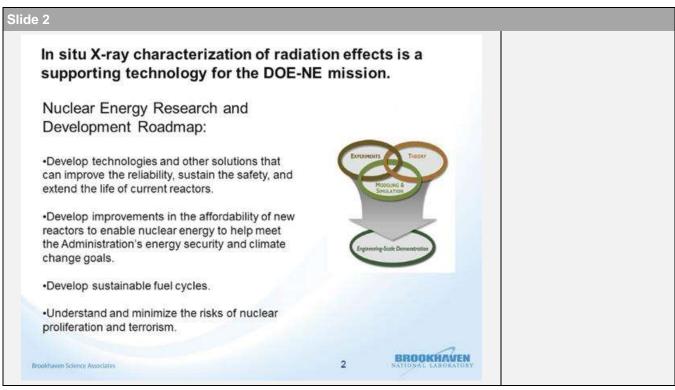


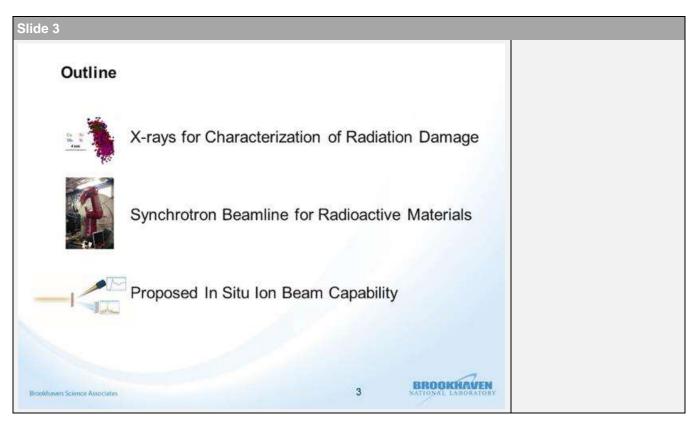


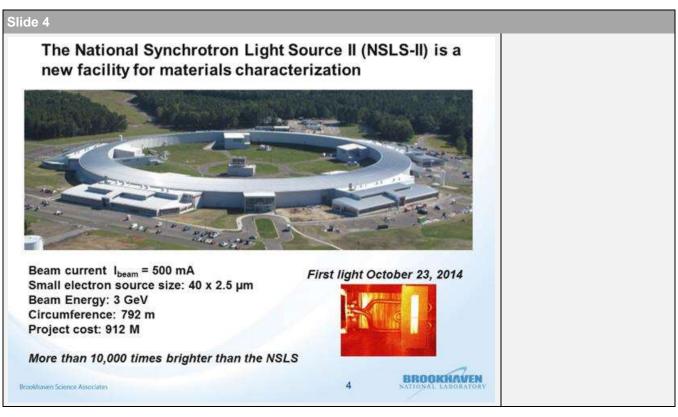
Presentation: In-Situ X-ray Characterization of Microstructural Evolution

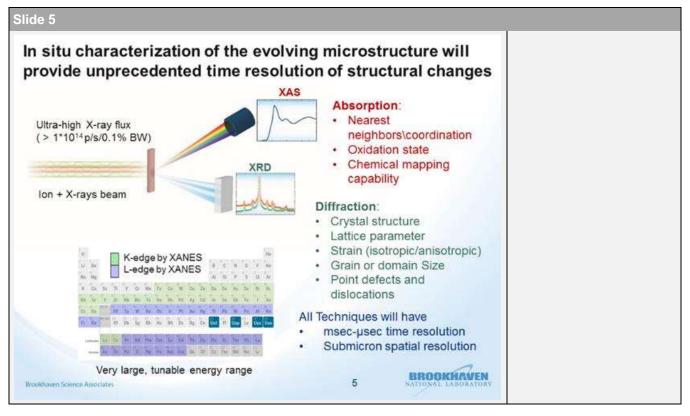
Lynne Ecker

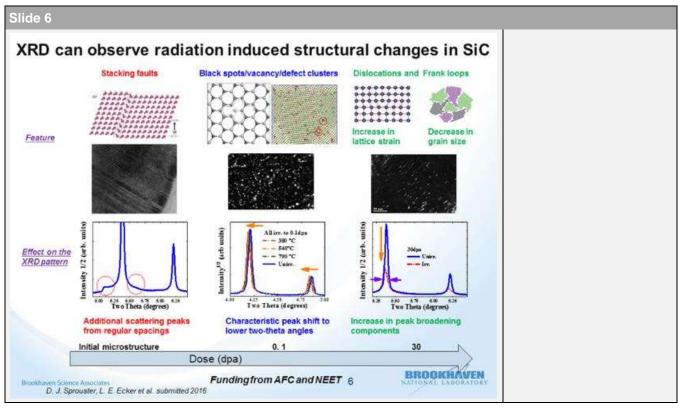


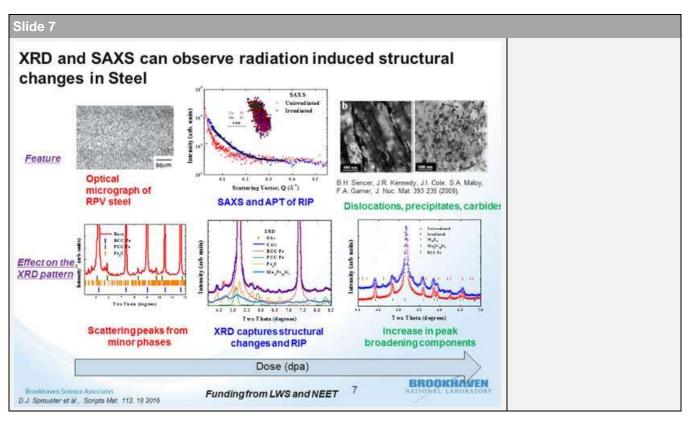


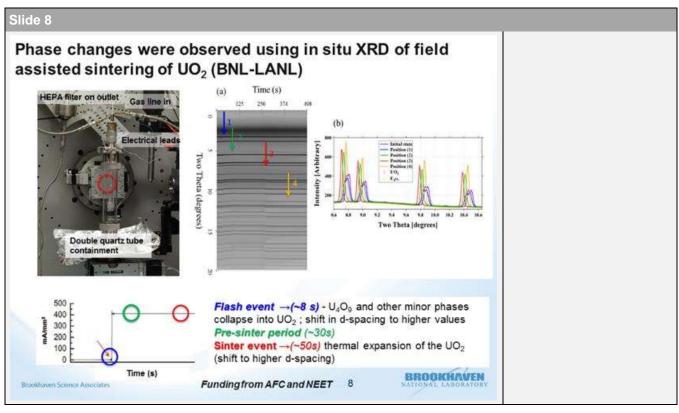


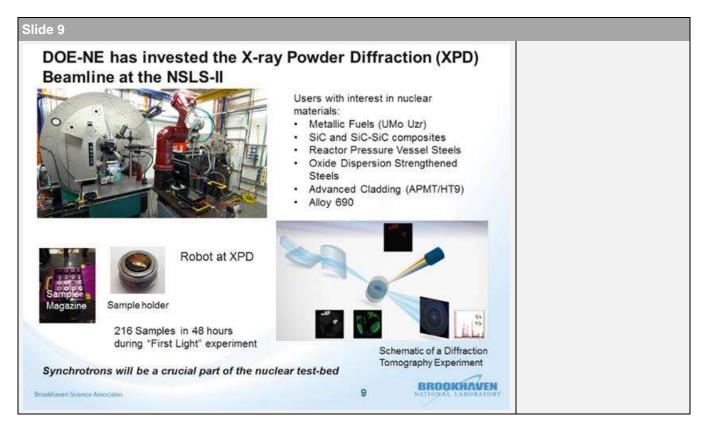


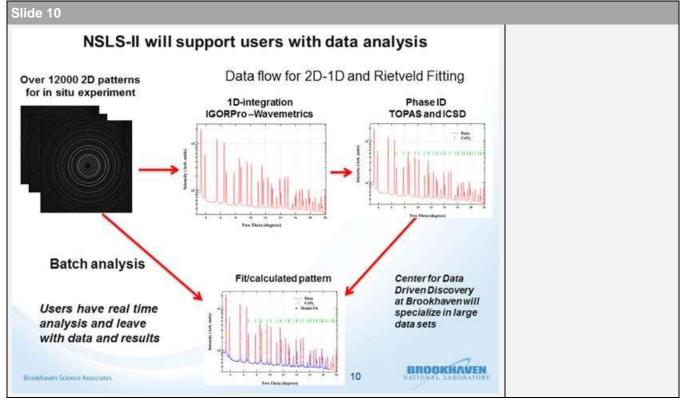


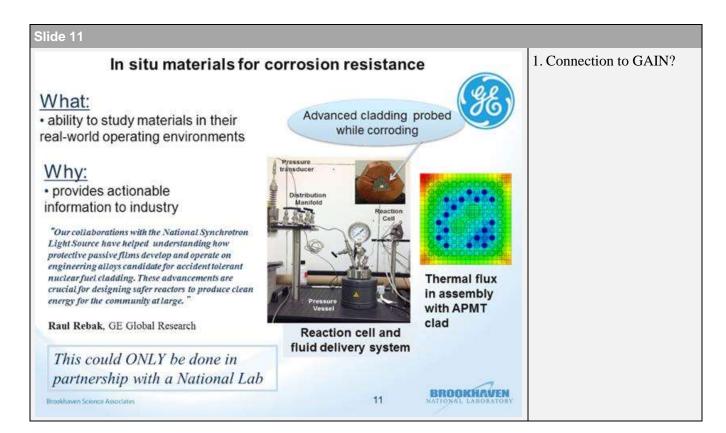


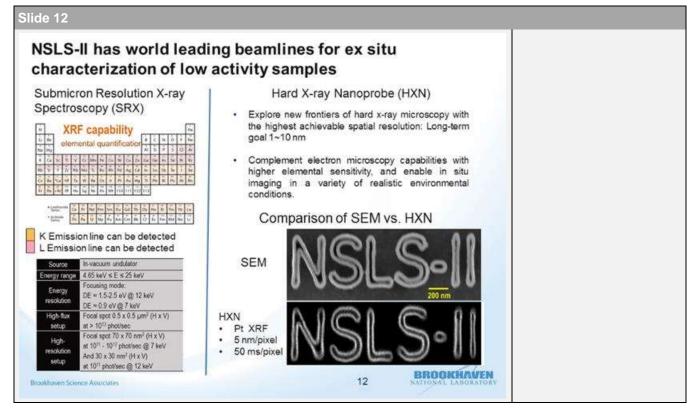


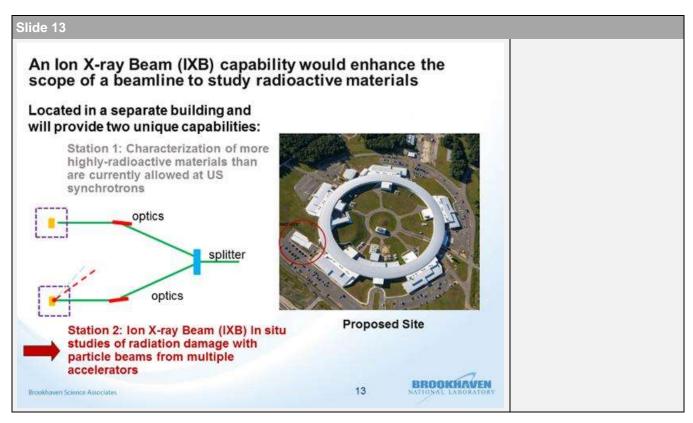


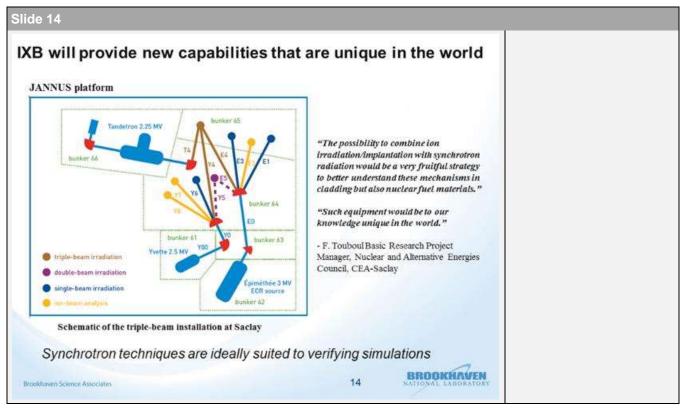


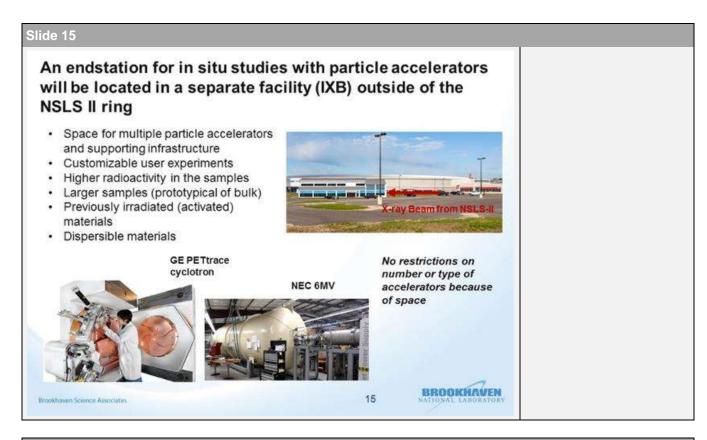


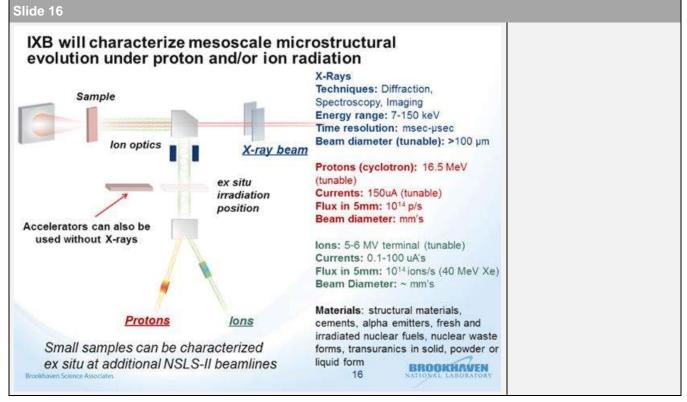


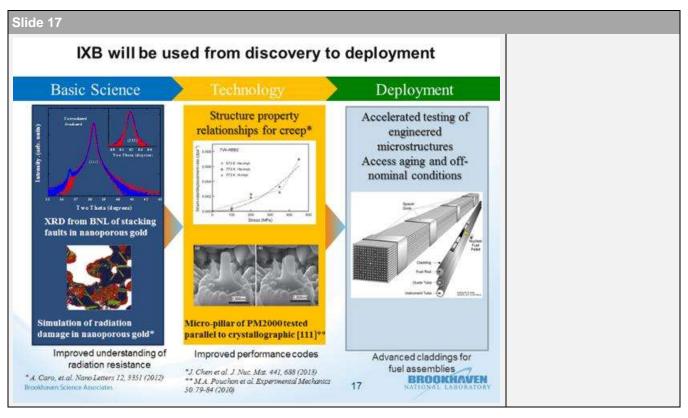


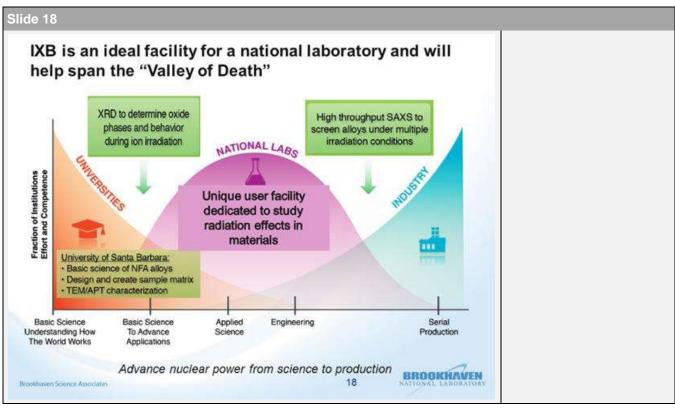












Access IXB is provided through a DOE User Facility: the NSLS-II

- · Access to world-leading, complementary beamlines at NSLS-II
- Accommodate industry (rapid access to beamtime, remote access, proprietary)
- · NSLS-II 5000 hrs/year
- · DOE user facility with support infrastructure, guest center, training, accommodations, established proposal process
- · Radiation handling, shipping and receiving, remote hot cells
- Maintenance on x-ray source from NSLS-II

· New directorate for data analysis









SRX

XPD

HXN

19

Brookhaven Science Associates

Slide 20

Criteria



Ability of the facility to produce results of high scientific merit and the potential to meet needs of DOE-NE and industry.



Provide a variety of ion irradiations



Irradiation environments and conditions.



Collect microstructural characterization data onsite and in-situ.



NE activities / volume of experiments that can be handled.



Unique capabilities of the facility including new technology



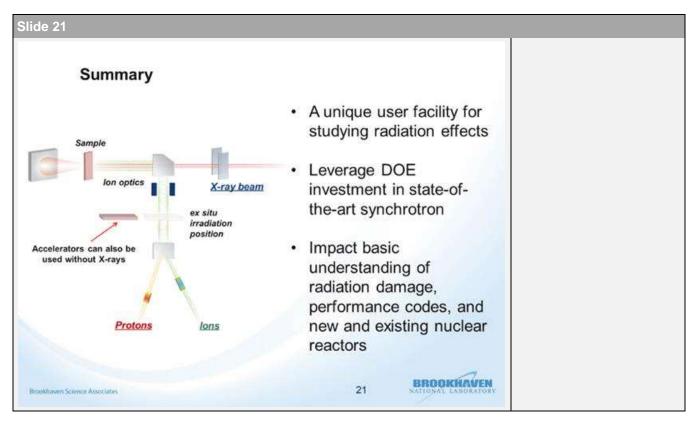
Handle radioactive materials in the beams and elsewhere onsite.

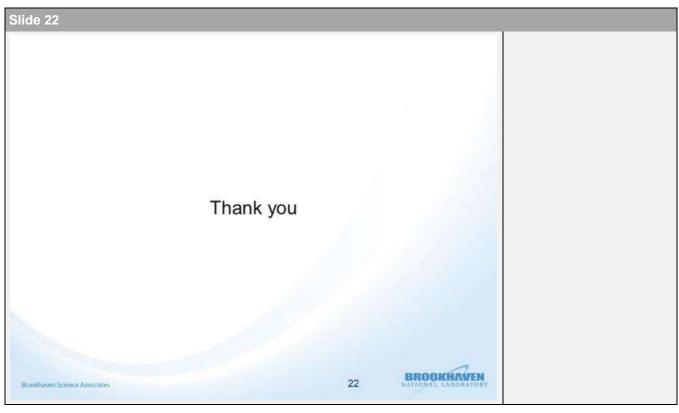


Produce high quality data that can support verification and validation for modeling and simulation.

20

BROOKHAVEN

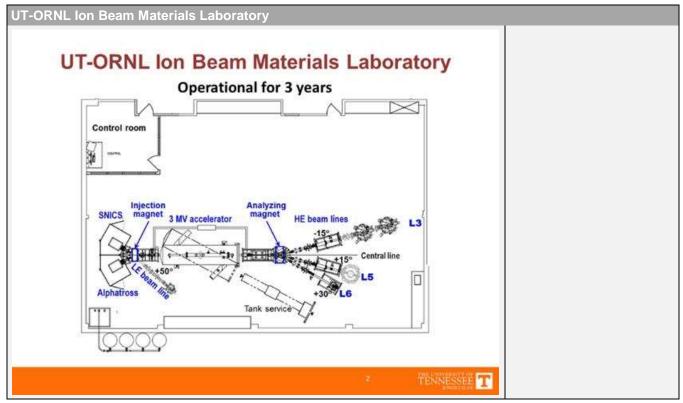


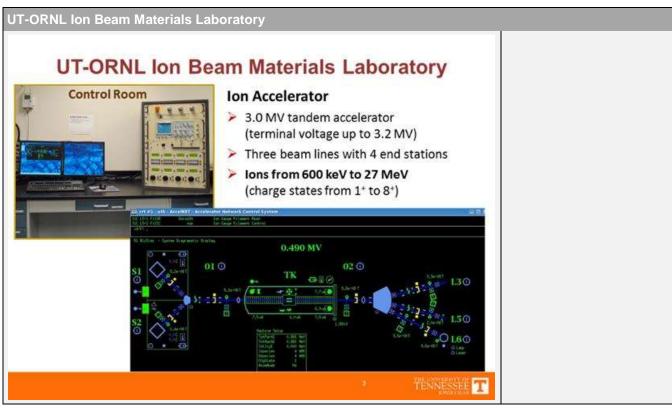


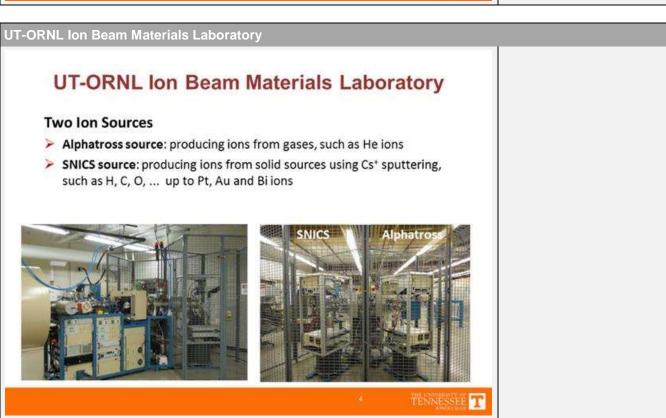
Presentation: Univ. of Tennessee IBML

William Weber

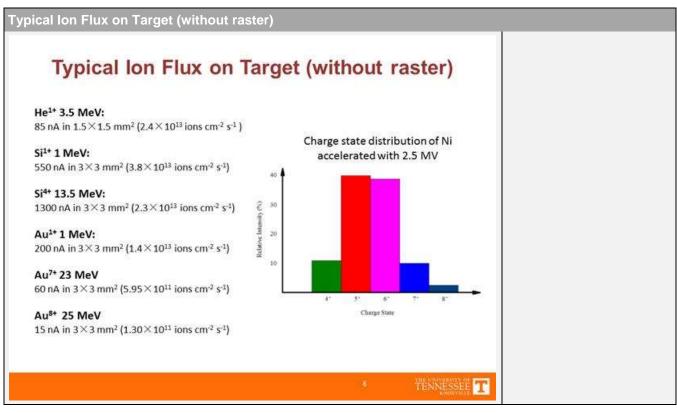












High-Energy End Stations

High-Energy End Stations

Station L3A: Radiation Effects - 100 to 1500 K

- > Manipulator has 1 axis of tilt and 3 axes of translation
- > Beam rastering capability
- > Time-of-Flight spectrometer (ERDA, electronic stopping, etc.)

Station L3B: Closed-cycle helium system (25 to 300 K) - Under testing

- > Manipulator has 3 axes of rotations and 3 axes of translation
- > IBA capabilities
- > 30 keV electron gun
- > In situ luminescence

Station L5: Radiation Effects - 150 to 1000 K

- Manipulator has 3 axes of rotations and 3 axes of translation; ideal for channeling measurements
- > Beam rastering capability
- > IBA capabilities

Station L6: Ion Beam Analysis (300 K)

- > Designated for routine, rapid analysis.
- > A large number of samples can be mounted on two sample holders
- > Equipped with standard IBA capabilities, e.g. RBS, NRA, ERDA, PIXE

No Radioactive Materials at this Time!



UT-ORNL IBML End Stations

UT-ORNL IBML End Stations





UT-ORNL IBML Endstations

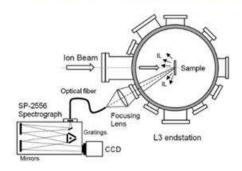
UT-ORNL IBML Endstations





In Situ Ion-Beam Induced Luminescence

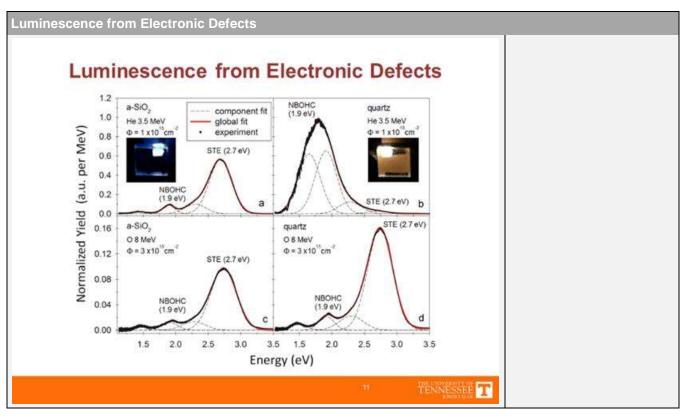
In Situ Ion-Beam Induced Luminescence

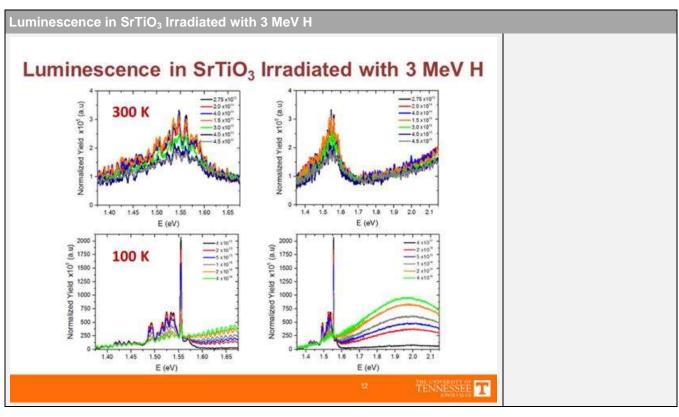


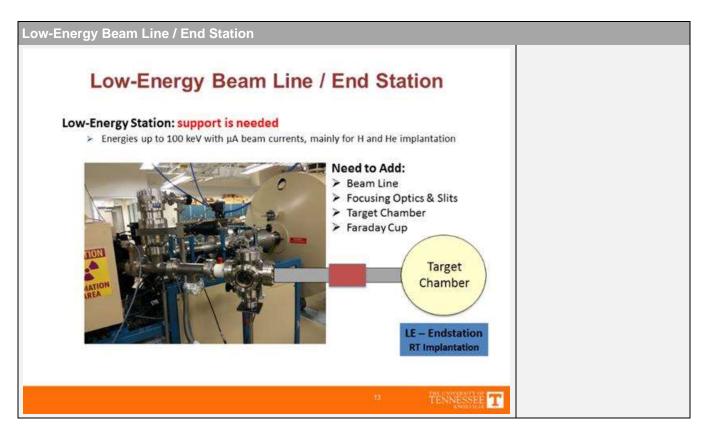


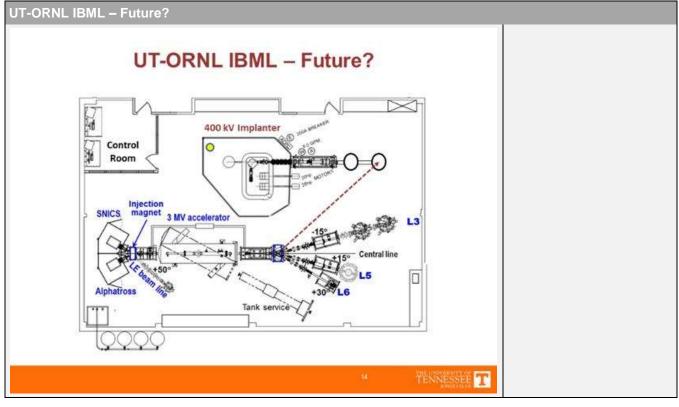
- Light emitted from sample transmitted through silica window port (at 150° with respect to ion beam direction)
- Light collected using 25mm diameter, 4 cm focal-length silica lens into silica optical fiber (1 mm diameter)

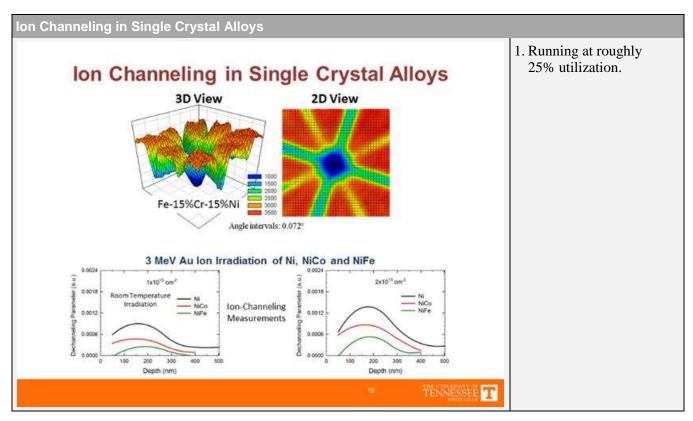
TENNESSEE T

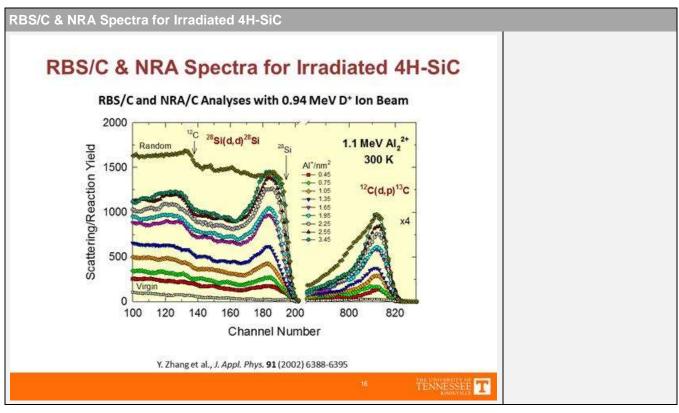


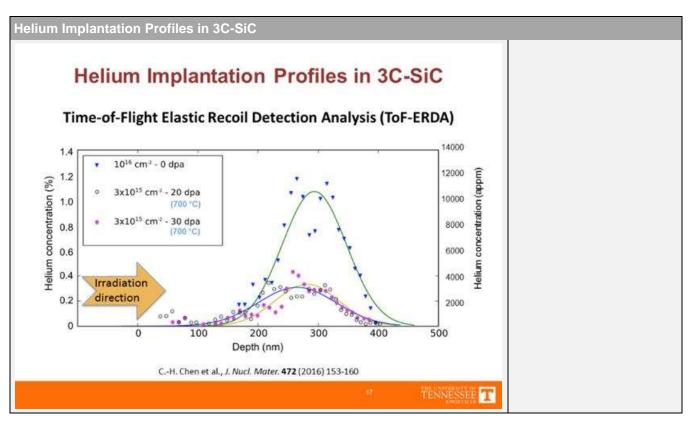


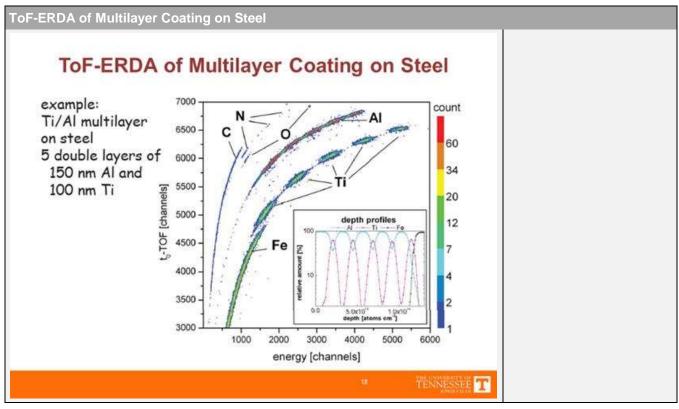


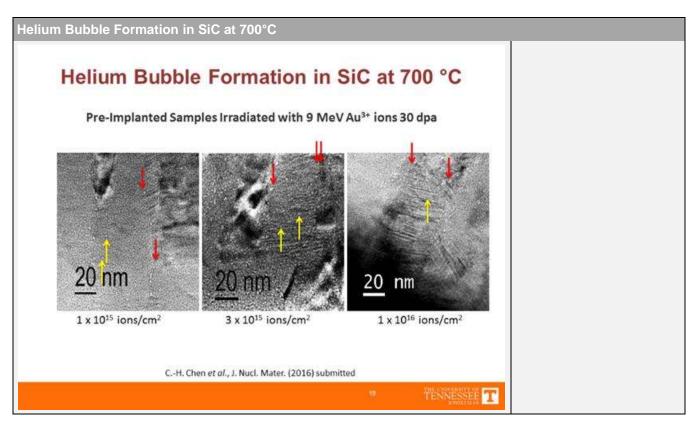


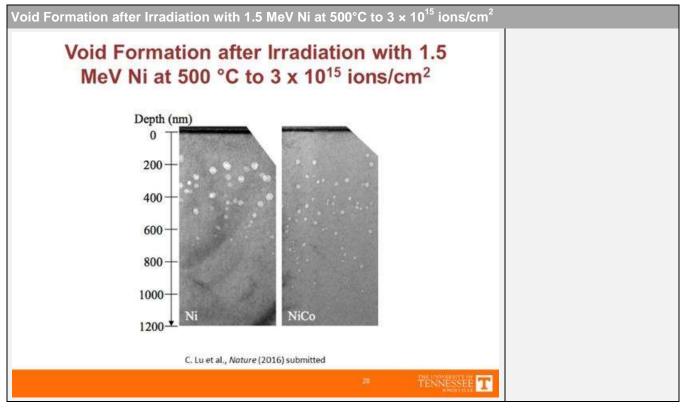












Users University of Tennessee – MSE, NE, Physics Oak Ridge National Laboratory North Carolina State University University of Michigan University of California – Irvine Missouri University of Science & Technology Kyushu Institute of Technology Kyoto University University Paris – Sud (Orsay)

Presentation: Edwards Accelerator Laboratory at the University of Ohio Steve Grimes

Edwards Accelerator Lab Ohio University, Athens Ohio INSTITUTE OF NUCLEAR & PARTICLE PHYSICS PARTICLE PHYSICS Physics & Astronomy NSUF Workshop March 22:24:2016

Accelerator

Accelerator

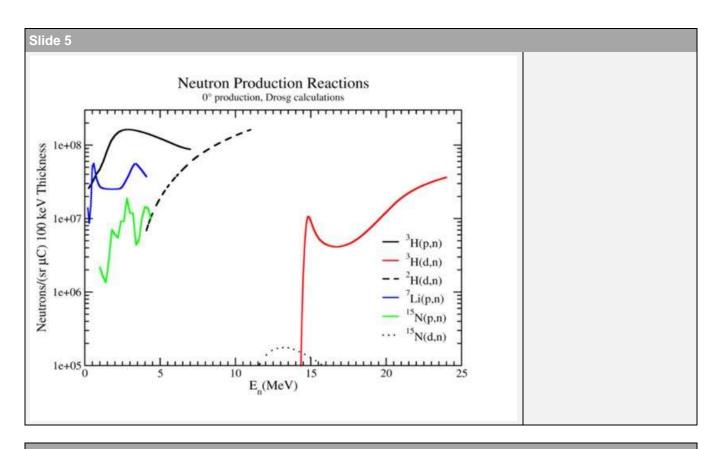
- Tandem van de Graaff with upgrade to pelletron.
- 4.5 MV Maximum Terminal Voltage
- Design maximum current 200 μ A.
- Pulsing 200 ns to 204.8 μs in factor of 2 increments.
- Provides beams of: ¹H, ²H, ³He, ⁴He, ⁶Li, ⁷Li, ¹⁰B, ¹¹B, ¹²C, ¹³C, ¹⁶O



Neutron Source Reactions

Neutron Source Reactions

- Monoenergetic Sources: ³H(p,n),²H(d,n),
 ³H(d,n), ⁷Li(p,n),¹⁵N(p,n),¹⁵N(d,n)
- Both ³H gas targets and ³H solid targets are available
- White sources with stopping targets:
 ⁹Be(p,n), ⁹Be(d,n), ¹⁰B(d,n), ¹¹B(p,n), ¹¹B(d,n),
 ¹³C(p,n), ⁹Be(α,n), ¹³C(α,n), ¹⁹F(p,n), ²⁷Al(d,n),
 V(d,n)



Neutron Capability

Neutron Capability

- Beam Swinger allows angular distributions to be measured with one Time-of-Flight Tunnel flight path 4.5 to 30 meters , -4° < 0 < 158°.
- Beam Pulsing ~1 ns width for ¹H, ²H and ~2.5 ns for other beams.
- A dual gas cell is available for background subtraction.

Neutron Detectors

Neutron Detectors

- Liquid Scintillators NE213
- · Lithium glass
- BF₃
- Fission chambers- 235U, 238U

Advanced Method for Calibration

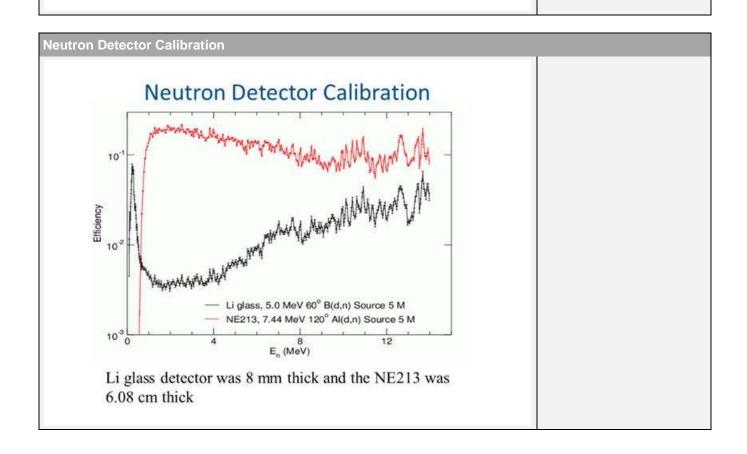
Advanced Method for Calibration

- The neutron spectrum for a stopping target using the 27 Al(d,n) reaction at E_d = 7.44.
- The spectrum has been measured at 120° using a ²³⁵U fission chamber.
- This spectrum can be used to calibrate a detector from 0.2 to 12 MeV in a short time.
- The NE213 efficiencies obtained by this method are close to the calculated efficiencies.

Lithium Glass Detectors

Lithium Glass Detectors

- The measured efficiencies of lithium glass detectors differ from the calculated shape from just the 6 Li(n, α) reaction.
- Contributions from ¹⁶O(n,n'γ) and ²⁸Si(n,n'γ) are important above 1.8 MeV.
- Detectors which have the same specification of ⁶Li content have efficiencies which varied by a factor of two at the 250 keV resonance.



Pulsed Neutron Spheres

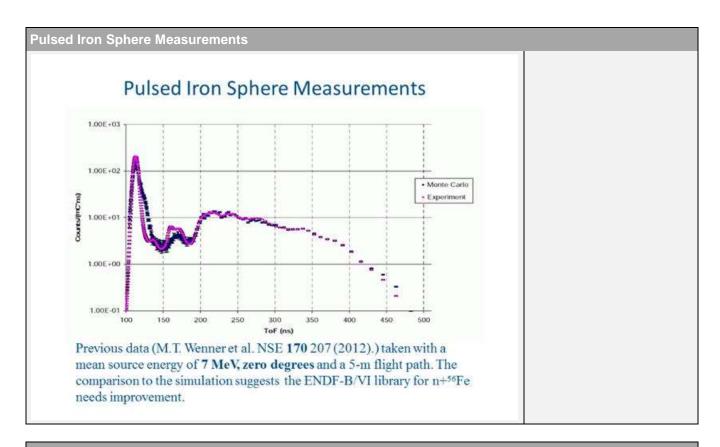
Pulsed Neutron Spheres

- A gas cell is placed in the center of a spherical shell with high purity material.
- The Time-of-Flight for the emerging neutrons is measured with a neutron detector.
- The spherical shell is typically 0.5 to 2.0 mean free paths thick.
- The energy of the neutrons cannot be directly measured due to multiple scattering.
- The experiment is modeled with Monte Carlo to calculate the arrival time spectrum

The Iron Sphere Setup

The Iron Sphere Setup





Published Iron Sphere Results

Published Iron Sphere Results

- At E_n = 1 MeV the spectrum is in agreement with ENDFB_VII.
- For En > 5 MeV, the sphere results disagree with predictions.
- Modifications are required for the ENDFB_VII evaluation.
- Elements that need to be checked are C, Zr, U and Pu.

Time-of-Flight, Energy spectrometer

Time-of-Flight, Energy spectrometer

- It is difficult to optimize for ΔE thickness for a ΔE-E telescope if both alphas and protons are detected.
- Measuring E and ToF allows the separation of the different particles emitted.
- This spectrometer has 10 instrumented angles and has 85 cm or 170 cm flight paths.
- Additional neutron or gamma detectors can be added.

Facility Upgrades-Negative Ion Source

Facility Upgrades-Negative Ion Source

- Torvis (NEC) estimate \$500,000
 - $-40~\mu\text{A}$ He
 - 100 µA H, D
- Aphatross(NEC) \$250,000
 - $-4~\mu A$ He
 - $-10~\mu\text{A}$ H, D
- The ion optics are being checked for compatibility with our accelerator

Other facilities

Other facilities

- Two spectrometers available for (n,Z) reactions.
- · Facilities for surface science measurements
- A code which allows correct calculation of cross sections using the Hauser-Feshbach formalism for deformed nuclei.

Materials Science with the Application of Nuclear Physics

Materials Science with the Application of Nuclear Physics

- Nuclear Science
 - · Detection of fissile materials
 - Neutron Resonance Radiography
 - Neutron Imaging and Tomography
 - Neutron Detector development and calibration
 - Materials for Nuclear Reactors
 - Neutron Induced Single Event Upsets
 - Measurement of the p, d and t, alpha elastic recoil crosssections
 - Nuclear Reaction Analysis

Materials Science with the Application of Nuclear Physics (cont.)

Materials Science with the Application of Nuclear Physics (cont.)

- Other materials science techniques
 - Proton Induced X-ray Emission (PIXE)
 - X-ray Photo-electron Spectroscopy (XPS)
 - Low Energy Electron Diffraction (LEED)
 - In-situ growth and analysis of materials under ultra-high vacuum (uhv)

Summary

Summary

During the past 25 years-

- Numerous elastic and inelastic neutron scattering measurements completed.
- Measurement of Fe(n,p), Fe(n,α), Cu(n,p), Cu(n,α), Ni(n,p), Ni(n,α), completed.
- Stopping target neutron spectra measurements.
- Measurements and calculation of level densities.

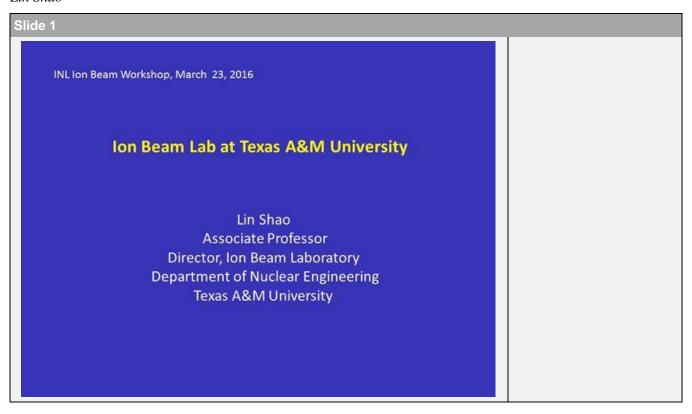
Summary – continued

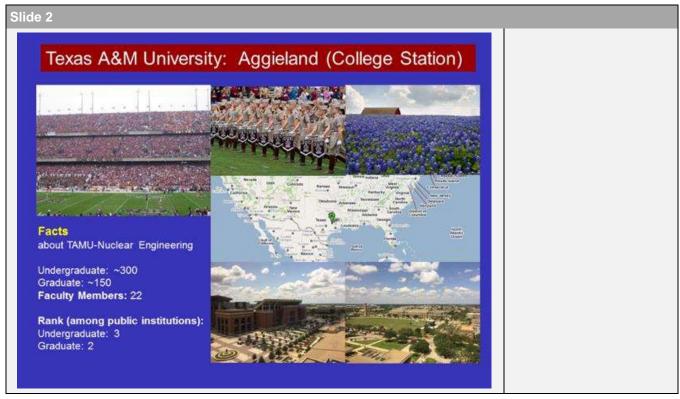
Summary-continued

- Collaboration with LLNL, LANL, ANL, Ohio State University, University of Michigan, Michigan State University, SUNY Geneseo, and Oak Ridge National Lab on neutron calibrations and activation capture measurements.
- Pulsed Sphere (Fe) measurements at 4 bombarding energies
- · Condensed Matter studies.

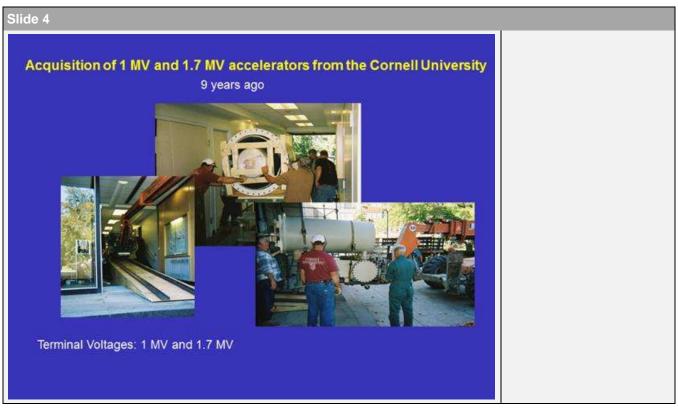
Presentation: Ion Beam Laboratory at Texas A&M University

Lin Shao





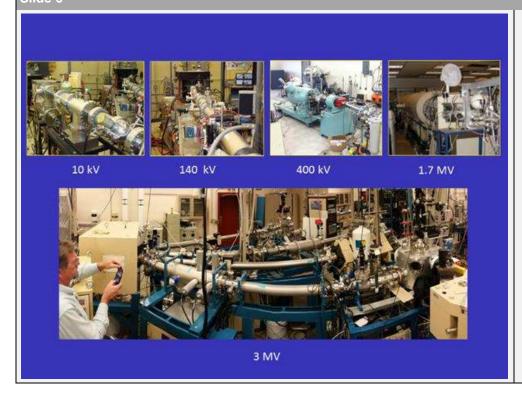


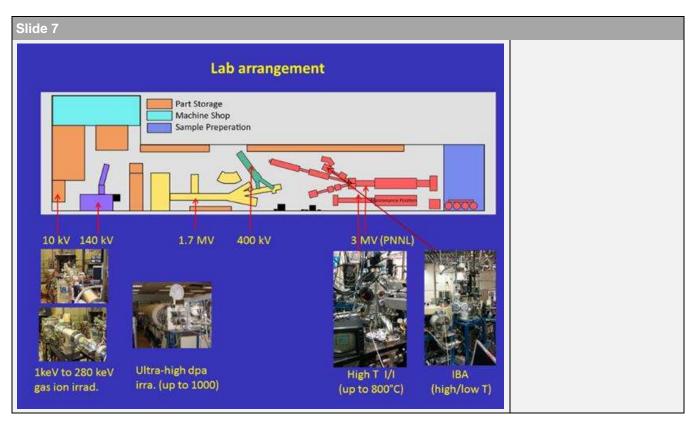


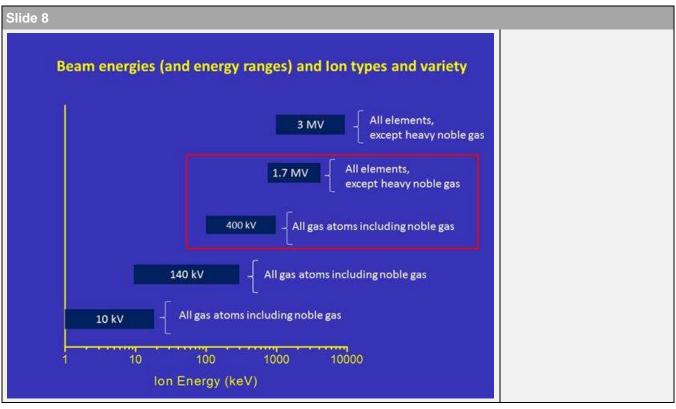
Acquisition of 3 MV NEC accelerator from PNNL (Aug., 2015)

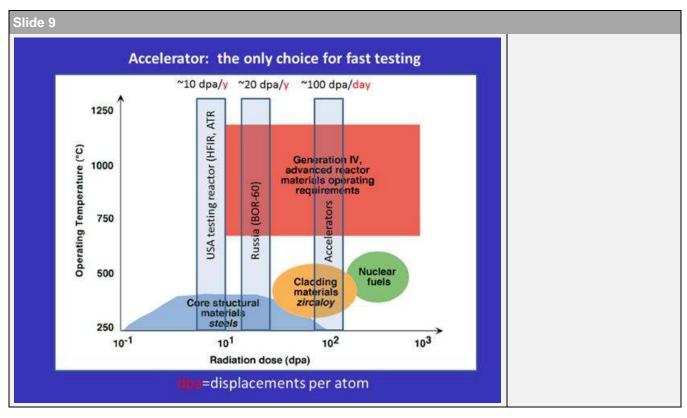


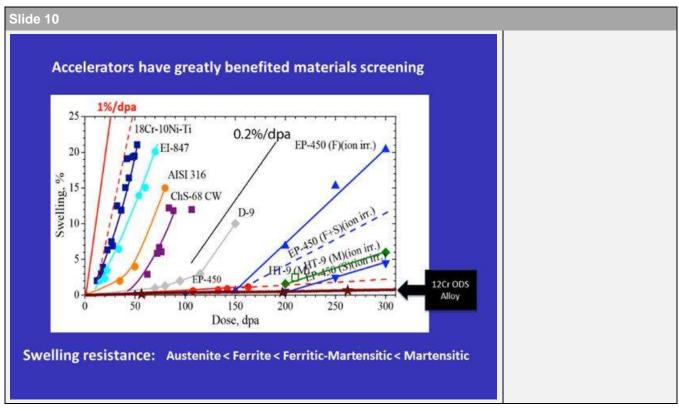
Slide 6

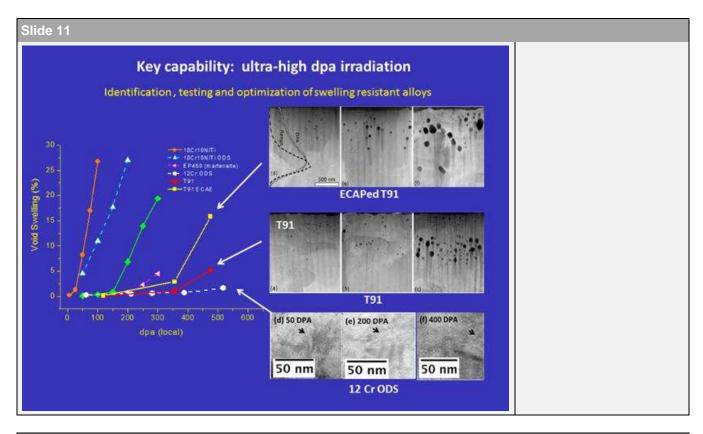


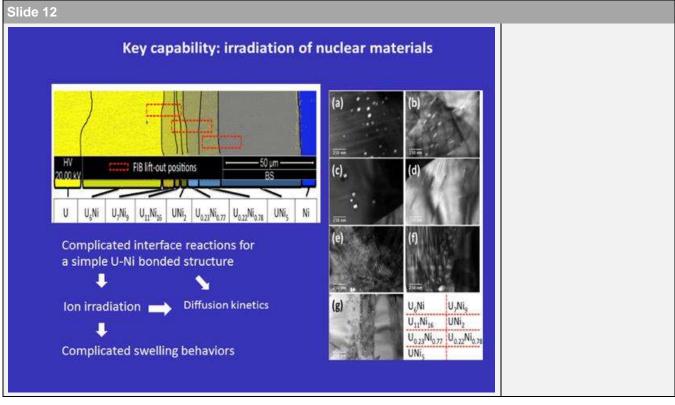












Slide 13

Ultra high dpa testing of nuclear materials

- 24/7 irradiation up to a few weeks
- Peak dpa in steels up to 1000

Proportion of time to be allocated to direct NE mission work

- ~100% for 3 MV Accelerator
- ~50% for 1.7 MV Accelerator

Slide 14

Radiation level allowed for samples <0.1 mCi

Types of sample materials allowed

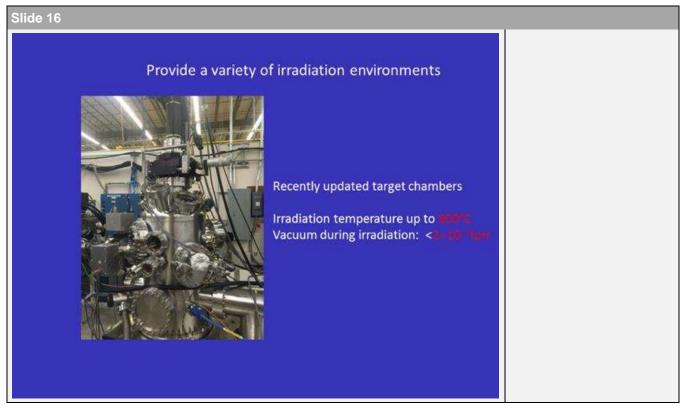
- Depleted uranium
- Reactor treated stainless steels

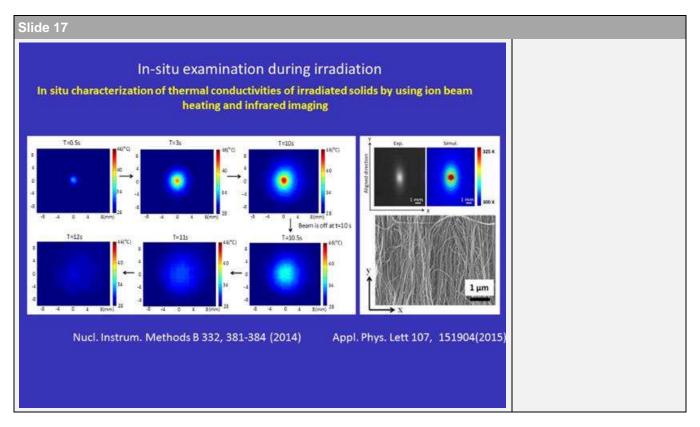
Supporting infrastructures (for radiative materials)

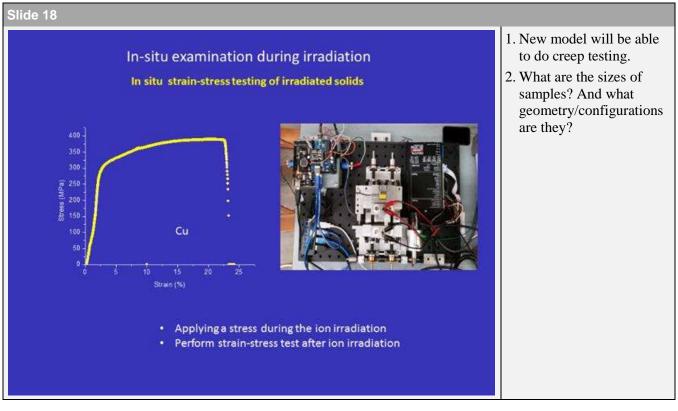
- Cutting and polishing of radioactive materials
- SEM characterization of radioactive materials

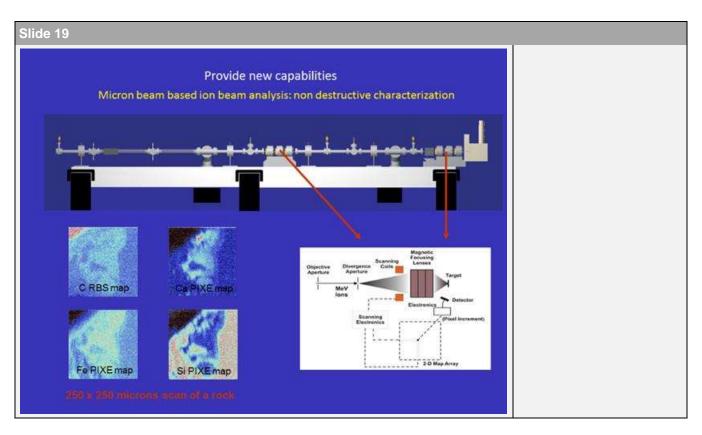
Supporting infrastructures (for nonradioactive materials) FIB, TEM, SEM, too much to list...

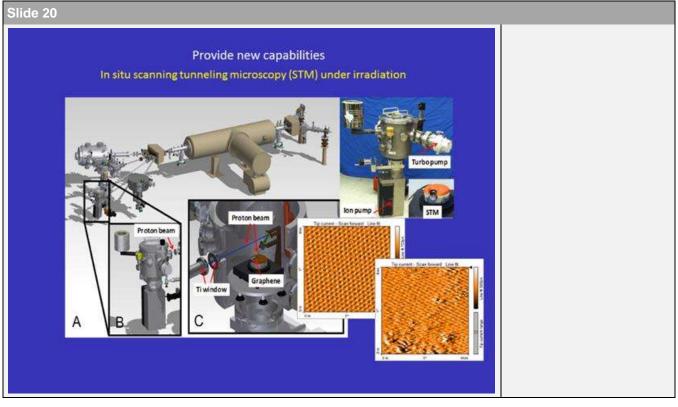


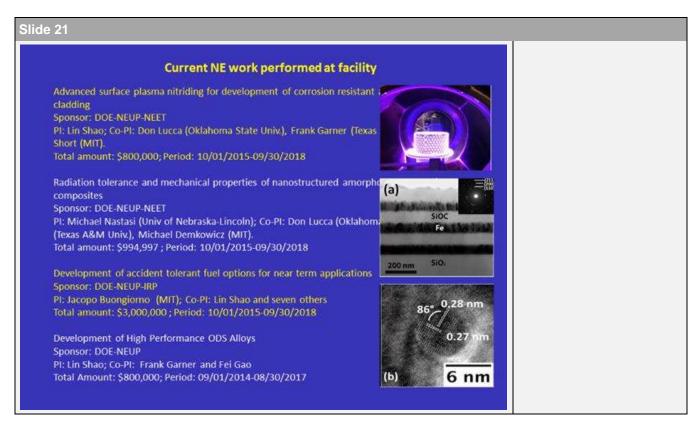


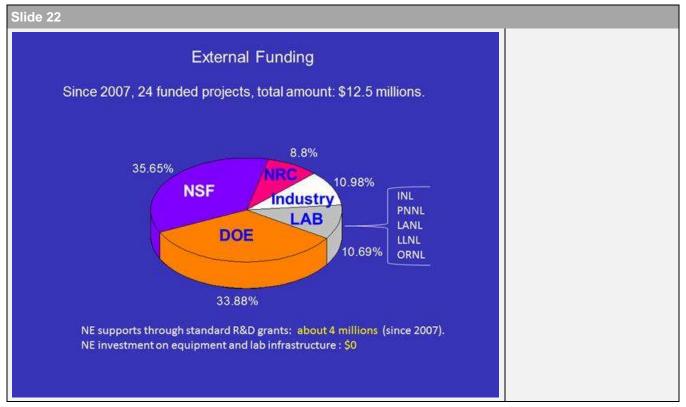




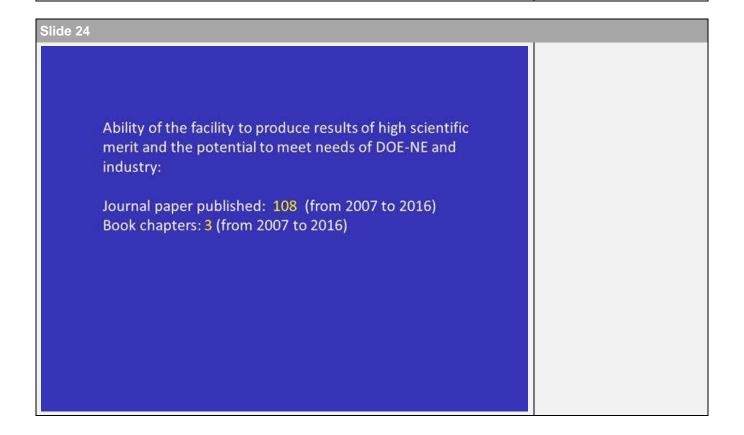


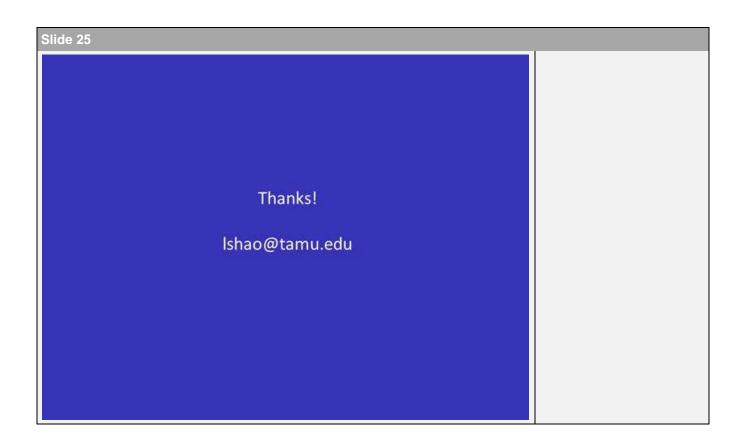






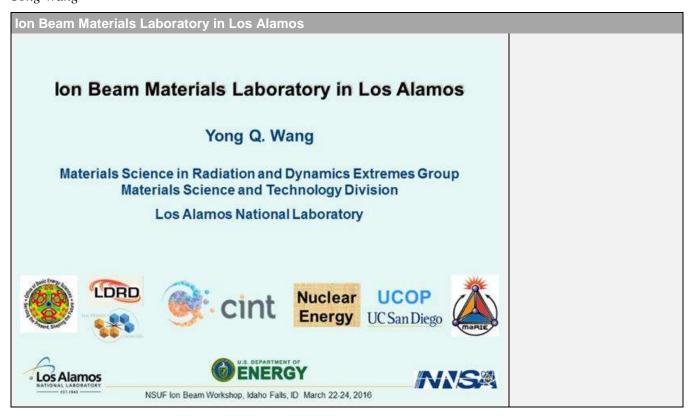
Slide 23 **Key Capabilities** (a) Various Ion Beam Analysis Rutherford backscattering spectrometry (RBS) · Elastic backscattering spectrometry (EBS) · Elastic recoil detection (ERD) · Particle induced X-ray emission (PIXE) Nuclear reaction analysis (NRA) (b) Various Ion Beam Modification of Materials · Ion implantation Ion smoothing Ion mixing Defect engineering (c) In situ Sample Characterization · Ion beam analysis + ion irradiation, simultaneously. (d) Multiple Ion Beam Irradiation · Ion irradiation with different ions at different energies, simultaneously. (e) Prolonged Ion Irradiation vs. Fast Ion Irradiation · Study radiation response of materials at different stages of structural transformation.

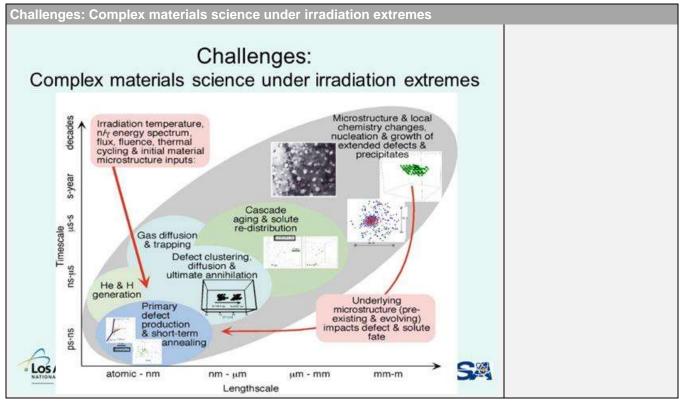


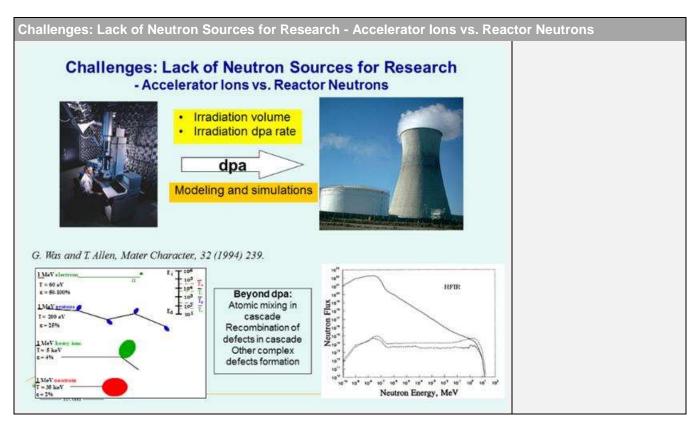


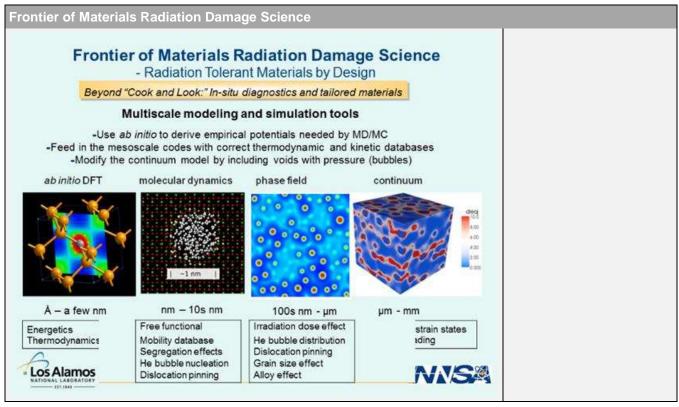
Presentation: IBML at LANL

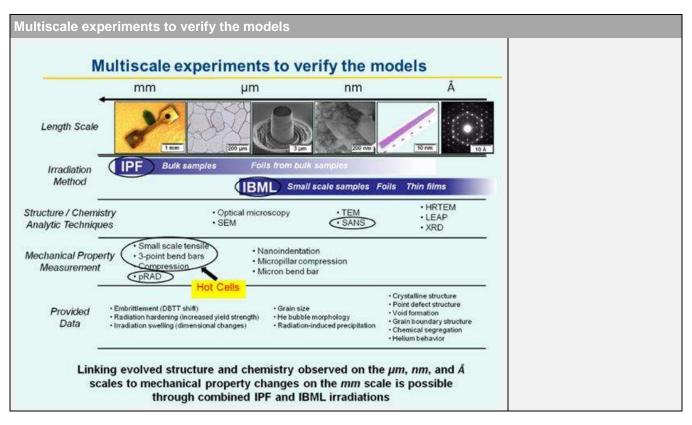
Yong Wang

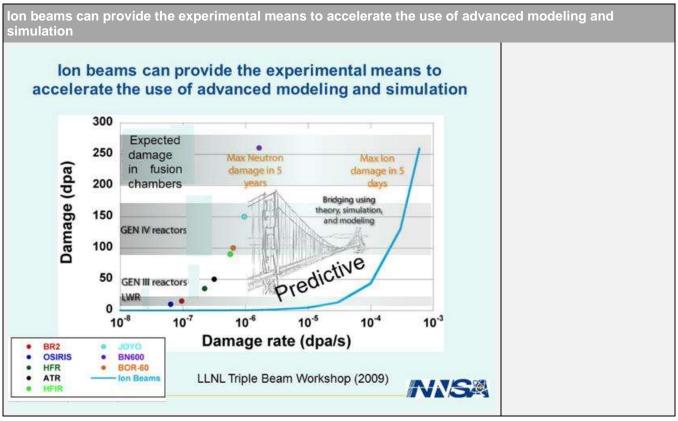




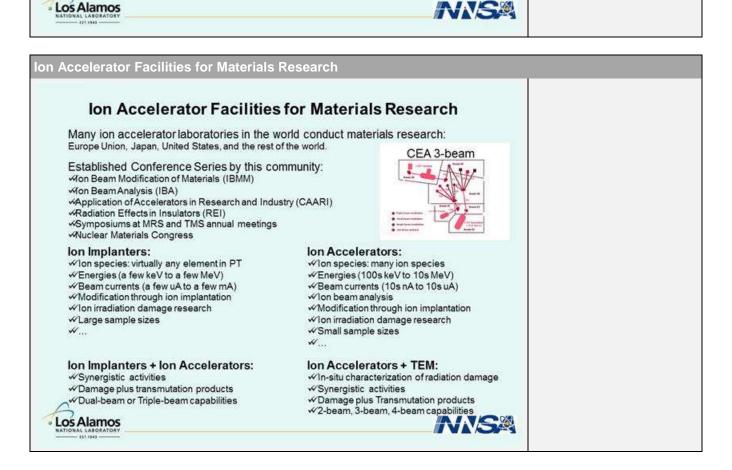








Ion - Solid Interactions Ion Beams Contribute to Nuclear Materials Research Ion - Solid Interactions Materials Analysis Materials Modification and Radiation Damage Secondary electron Incident particles STIM ERDA IBIC RBS and Interfacial Mixing PIXE Ion beams can contribute to materials research in three ways: ✓ Radiation damage effects in materials by ion bombardment ✓Materials characterization with ion beam analysis (IBA) techniques ✓ Materials modification and synthesis through ion implantation



Accelerator Beam Facilities at Los Alamos

Accelerator Beam Facilities at Los Alamos:

Los Alamos Neutron Science Center (LANSCE):

- √Los Alamos Meson Physics Facility (LAMPF)
- √800 MeV Linear Proton Accelerator
- ✓Manuel Lujan Neutron Scattering Center (MLNSC)
- ✓ Medical Radioisotope Production Facility (IPF)
- √Proton Radiography (P-Rad) Facility
- √Weapons Neutron Research (WNR) Facility

Dual Axis Radiographic Hydrodynamic Test Facility (DARHT):

- √18 MeV Pulsed Electron Beam Accelerator Facility (2 kA, 1.6 μS, 1.25 mm Spot)
- √X-ray doses: 100 rads @ 1m

Los Alamos Ion Beam Facility (IBF):

- √Two Accelerators: Van De Graaff (6 MV Vertical) + FN Tandem (9 MV)
- √Nuclear Physics Research Facility (protons, deuterons, tritons, alphas etc.)
- √Superconducting Solenoid Magnet Nuclear microprobe was constructed (1980)
- √Largely funded by weapons science programs
- √The facility was officially shutdown in 1995

Ion Beam Materials Laboratory (IBML) (since 1986)





LANSCE Experimental Areas

LANSCE Experimental Areas

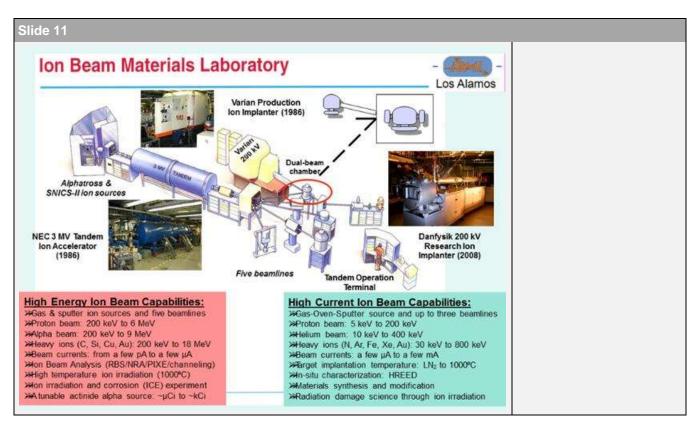
MaRIE 1.0 - 12 GeV e-Accelerator to produce XFEL source

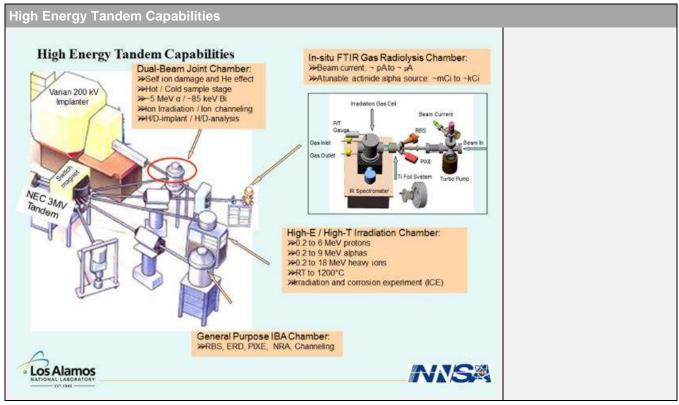


- Lujan Center
 - National security research
 - Materials, bio-science, and nuclear physics
 - · NNSA user facility
- =WNR
 - National security research
 - Nuclear Physics
 - · Neutron Irradiation
- Proton Radiography
 - National security research
 - Dynamic Materials science
 - Hydrodynamics
- ■Isotope Production Facility
 - · Medical radioisotopes

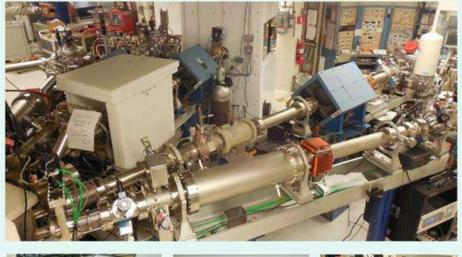








Slide 13









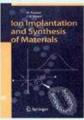
Ion Beam Materials Research at LANL (1986-2016) (Courtesy of Nastasi, Tesmer, Sickafus, Maggiore, Misra, Maloy, Uberuaga, Picraux, Jia, and others)

Ion Beam Materials Research at LANL (1986-2016)

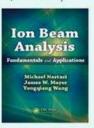
(Courtesy of Nastasi, Tesmer, Sickafus, Maggiore, Misra, Maloy, Uberuaga, Picraux, Jia, and others)











1995

1996

2007

2009

2014

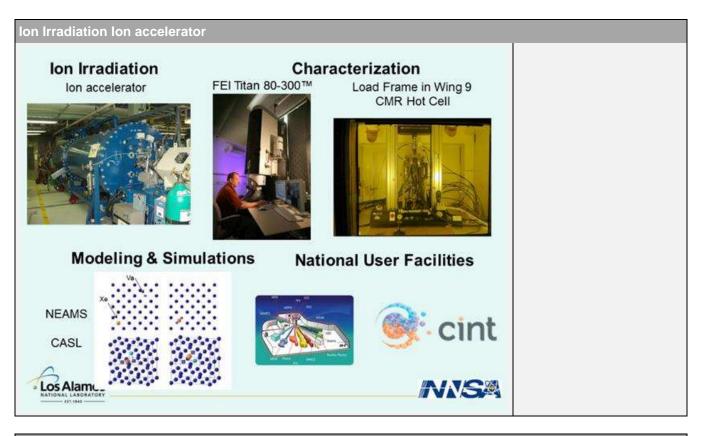
IBML related publications: Well over <u>1000</u> refereed papers have been published by LANL researchers using the IBML Facility since its inception, including journals like Science, Nature Materials, PRL, APL, Advanced Materials, JNM, JMR, NIM etc.

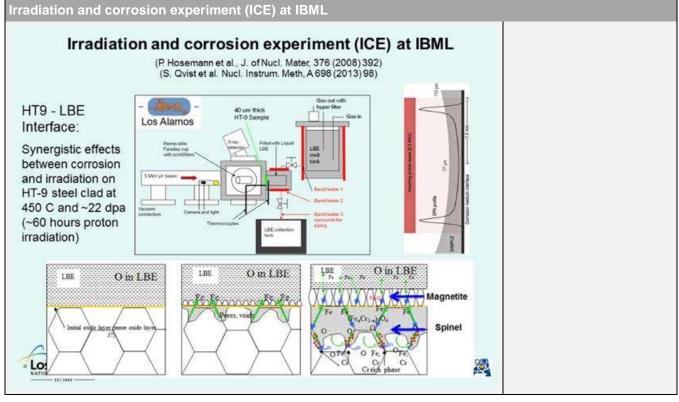
IBML user sponsored conferences: MRS symposium (1989), IBMM (1996), IIT (2002), IBA (2003), REI (2005), CAARI (2006-2014), IBA (2013).

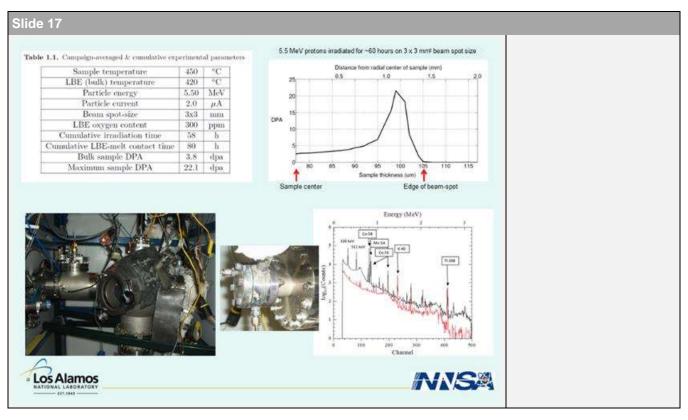
IBML supported programs: BES (EFRC, CINT, Single Pls), LDRD, NE (FCR&D, NEUP), Weapons, Space Programs, UCOP, WFO etc.

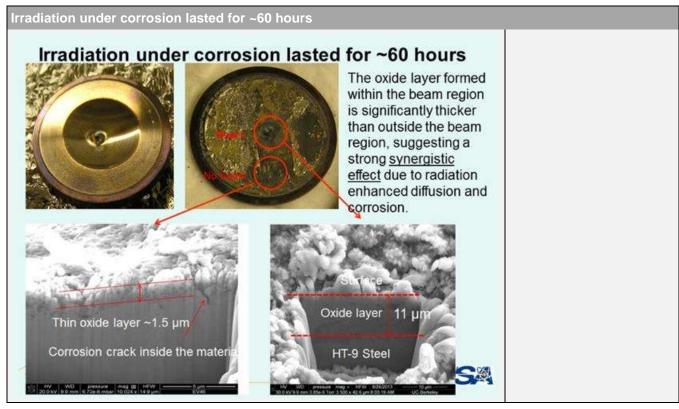


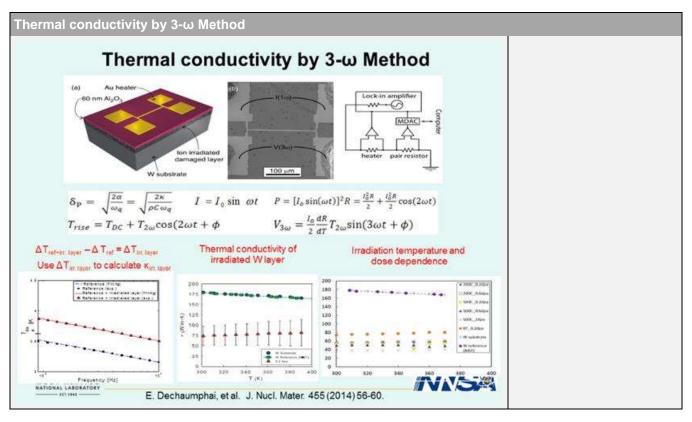


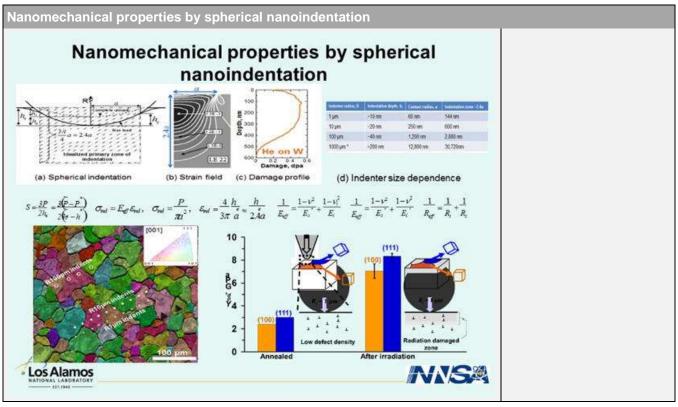


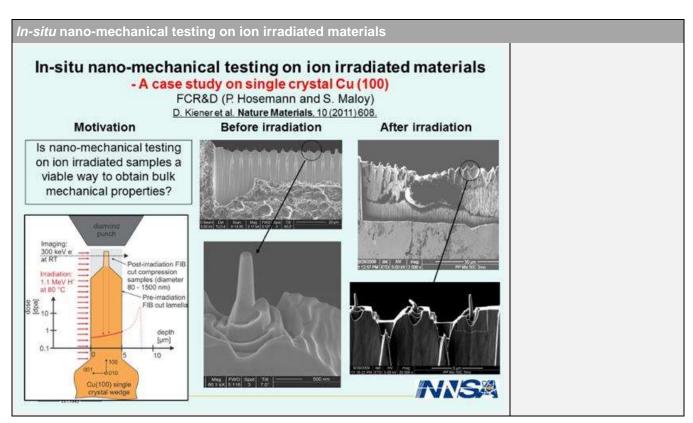


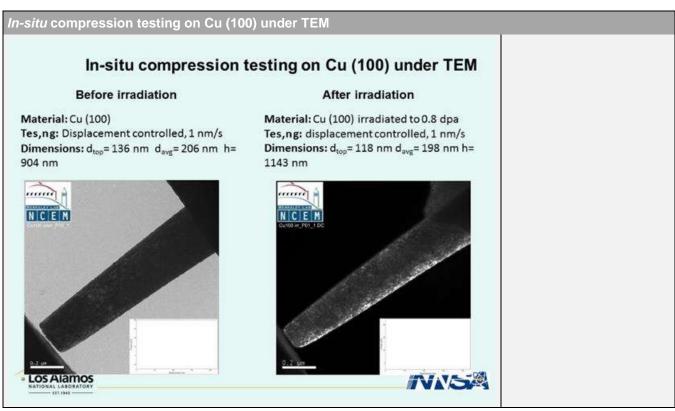


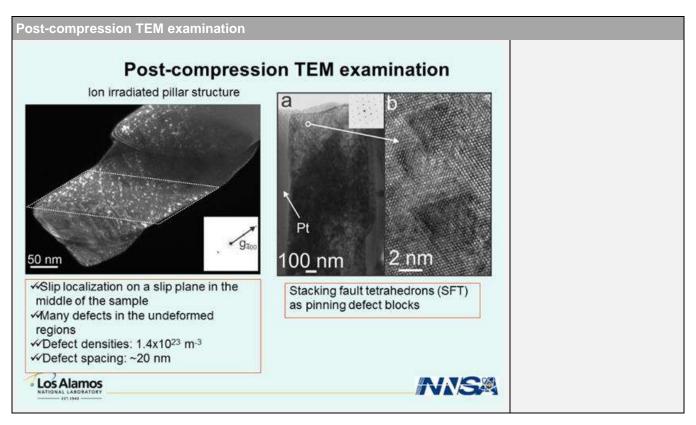


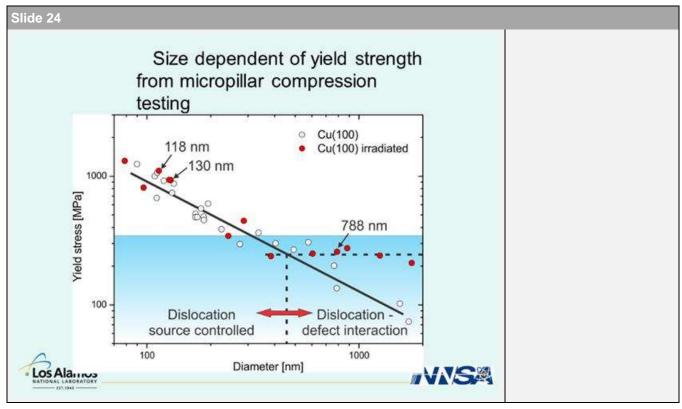


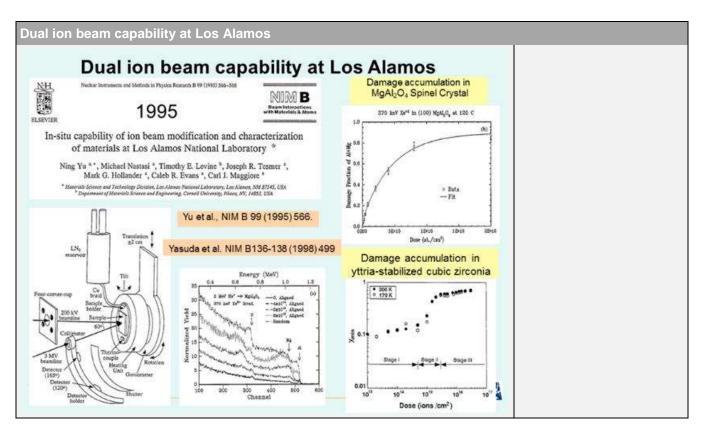


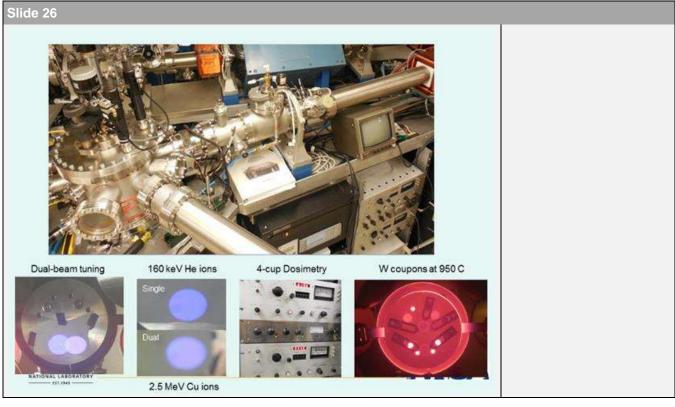


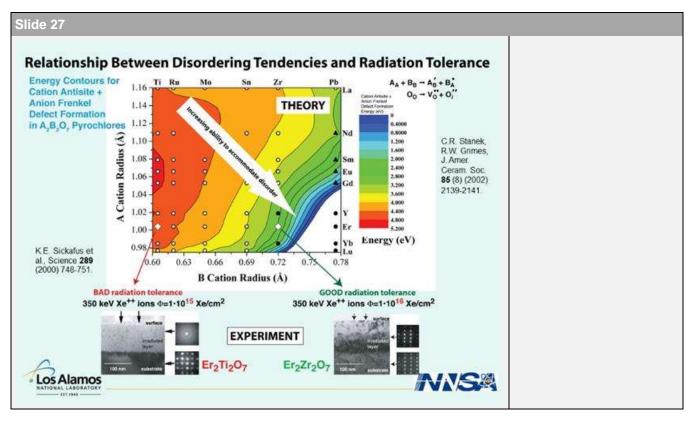


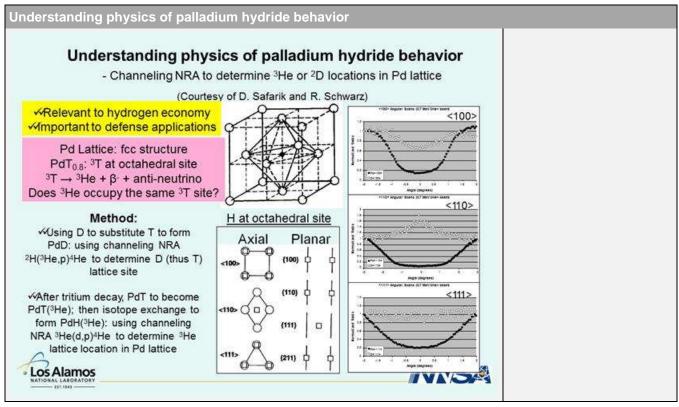


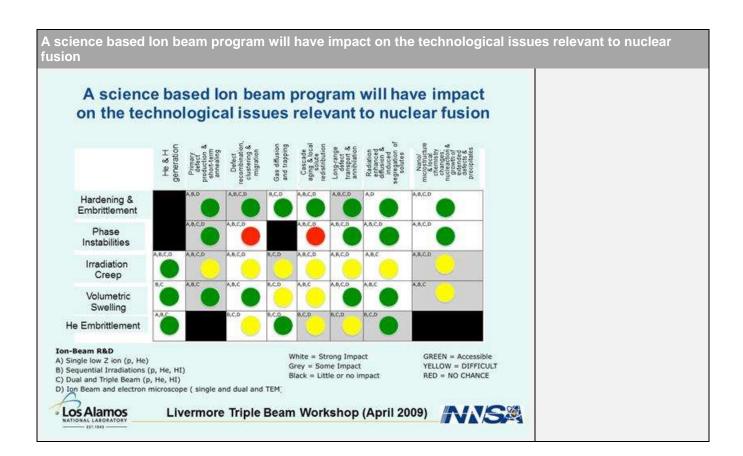






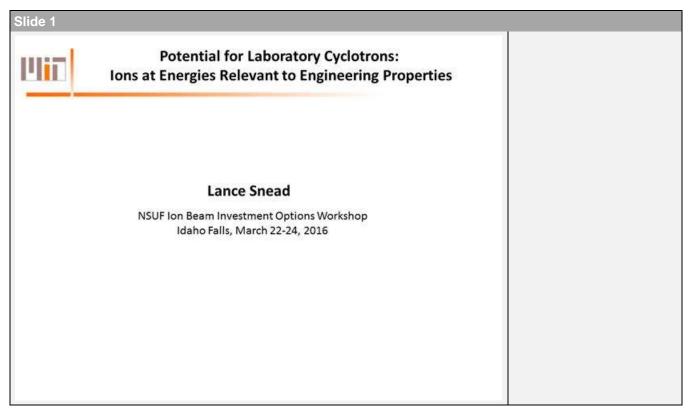


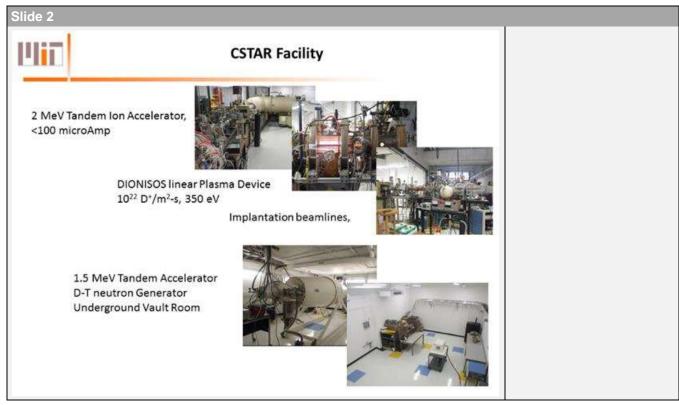




Presentation: Potential for Laboratory Compact Cyclotrons

Lance Snead

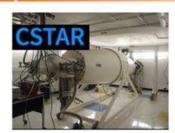




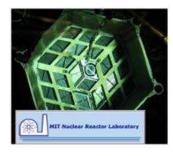
Slide 3



Facility (the capability) will Reside Within the Current MIT Ion Beam Laboratory with Access to Radiological Facilities







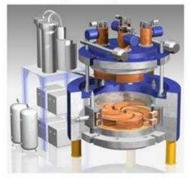


Slide 4



Facility (the capability) will Reside Within the Current MIT Ion Beam Laboratory with Access to Radiological Facilities

Cutaway of SC cyclotron





3 m diameter 250 MeV Superconducting cyclotron for proton therapy

Compact cyclotron evolution is presenting an opportunity for irradiation materials science:

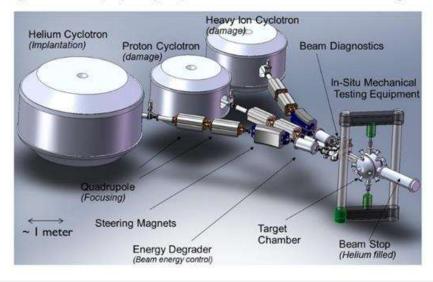
- compact footprint, reasonable capital procurement, low power consumption, continuous beam, high-energy.
- opportunity and goal: chart a path to irradiation of bulk samples while measuring physical of microstructural properties.
- Use data to seamlessly tie out understanding gained from low and intermediate energy ions to our limited data from neutron irradiated materials.

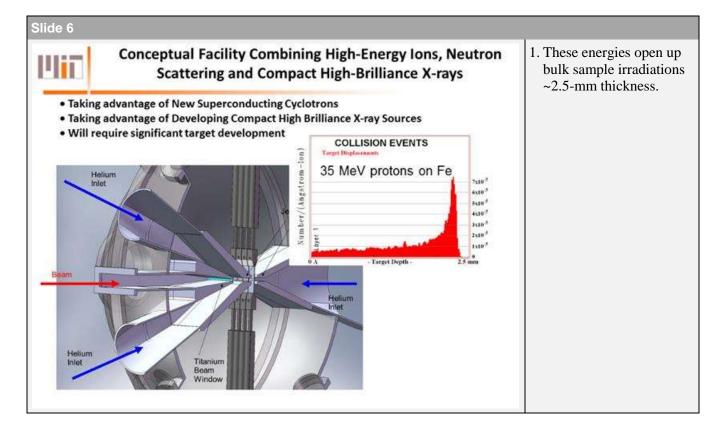
An internal MIT initiative for a combined Compact Cyclotron (10's of MeV), a compact High-brilliance X-ray capability, coupled with the native MITR neutron scattering beam.

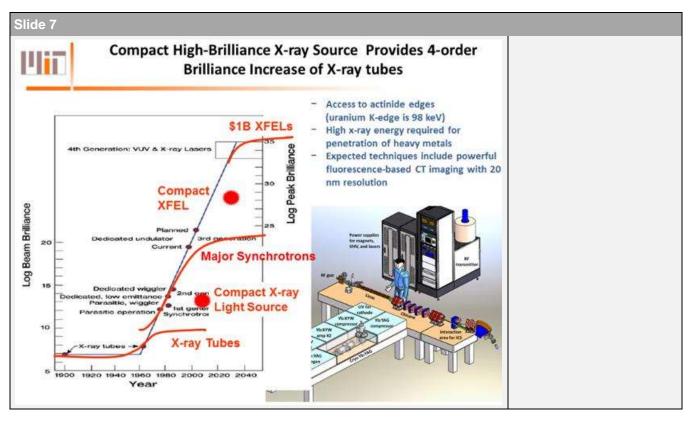


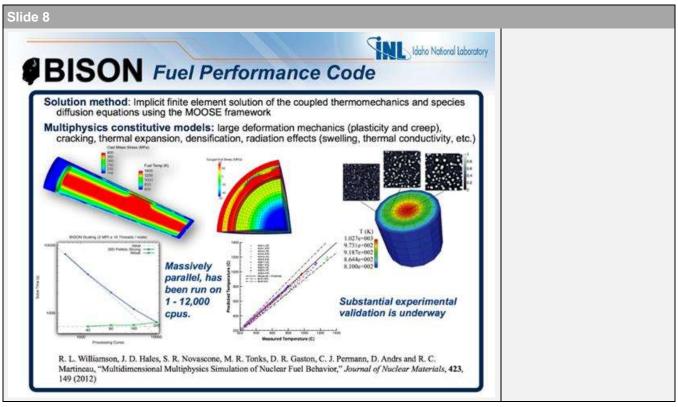
Long-Range Goal: Engineering Properties by Leveraging Coupled Modeling and Reduced Cyclotron Costs.

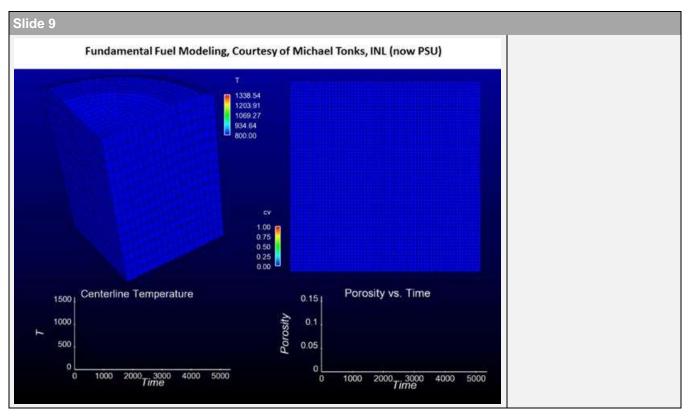
An internal MIT initiative for a combined Compact Cyclotron (10's of MeV), a compact High-brilliance X-ray capability, coupled with the native MITR neutron scattering beam.

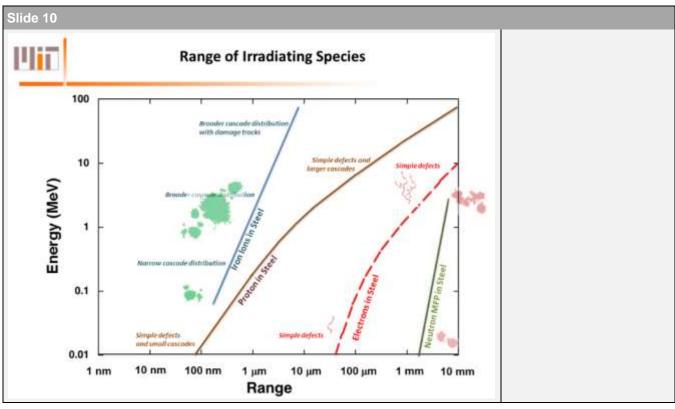


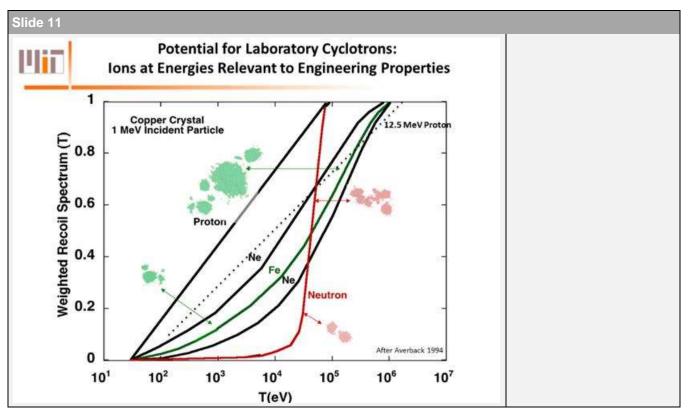


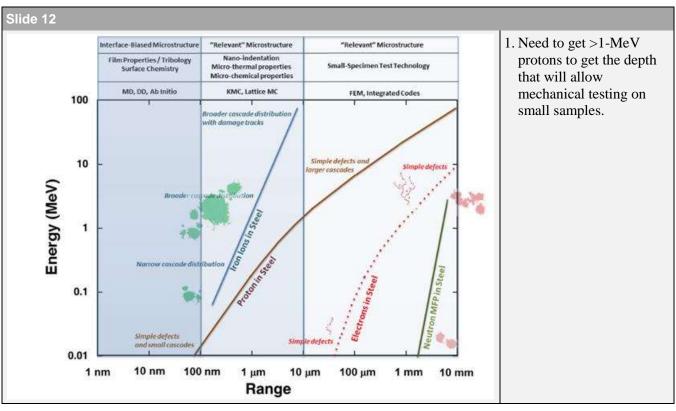


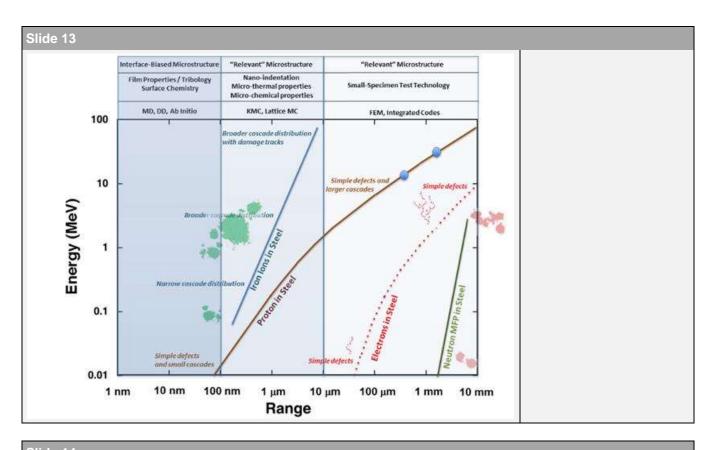














Near-term Goal: Demonstrate Compact Cyclotron to **Provide Relevant Engineering Data for Model Validation**

Proton+ (deuteron+) Energy 12.5 MeV (6.25 MeV)

Current <50 µA

Dimensions 0.96 m ϕ x 1.75 m Weight 1800 kg (4000 lb)

Power 208V 3-phase, 125A Peak power 35 kW (consumption)

Superconducting (always on) Magnets Magnetic field 4.5 T (internal); 50 gauss (1 m); 5 gauss (4 m)

Lab Under Construction Safety Evaluation Underway

Cryogenics Liquid-free; closed loop He

Internal (no external beam) Target

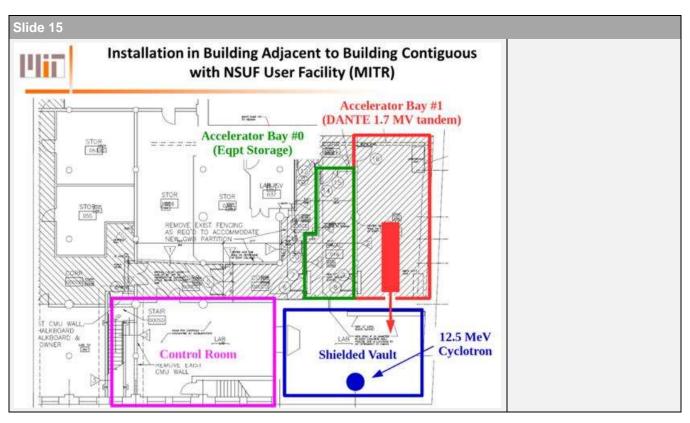
Target material Variable

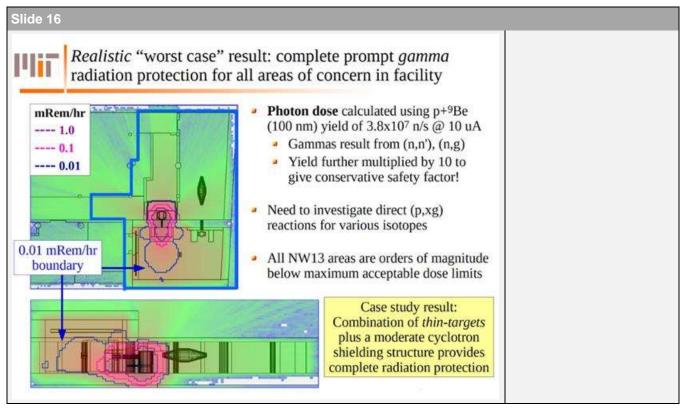


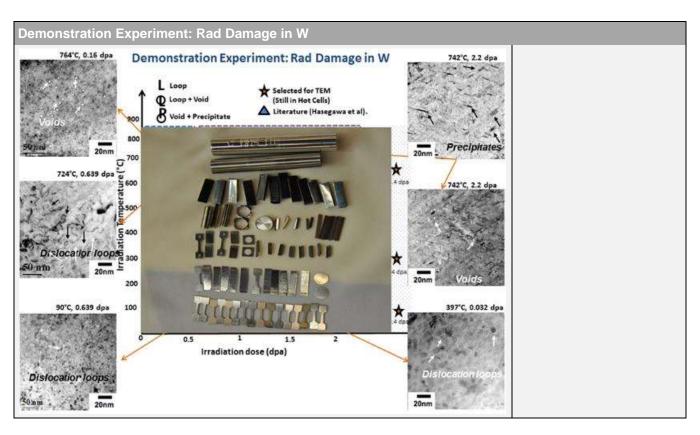
Instrument Installation April/May 2016

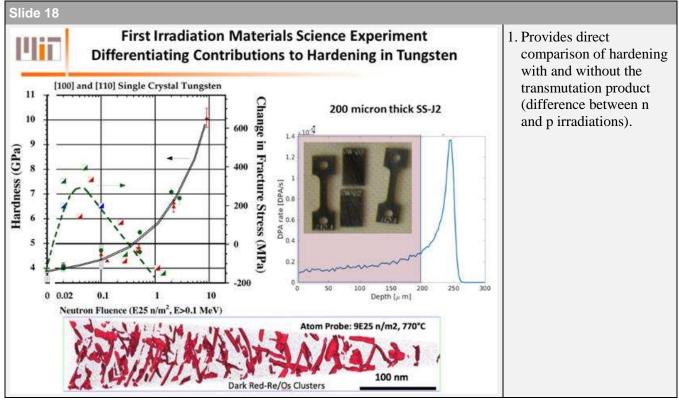
1. What is the timeframe for getting this operational? How long for the rest of the pieces?

2. [Lance Snead] The instrument will be operational within a month of delivery. Target design is underway. Construction of target thimble this summer. Irradiation late this year.









Slide 19



Concluding Remarks

- MIT will be exploring bulk ion irradiation and techniques to characterize samples
 while under irradiation. The ultimate goal is to provide a bridge from the bulk of
 irradiation materials science from low-to-intermediate energy ions to what is and
 will continue to be a limited set of neutron irradiation data.
- As a NSUF user facility and with a local reactor (MITR), comparison with neutron irradiated material will be straight forward.
- Given throughput issues, radiological issues and somewhat higher costs that the low-to-intermediate ion beam facilities such a "penetrating sources" will likely be unique facilities and their science largely guided by modeling goals.
- We will embark on the building blocks of such a facility with the development of compact high brilliance x-ray sources and demonstrating the usefulness of compact superconducting cyclotrons.
- It would be very useful to decide if such a facility is on critical path by carrying out a community roadmap exercise.

1. Primary purpose is to dead reckon the models—few facilities like this needed.

Appendix F Facility Ranking Exercise

Appendix F Facility Ranking Exercise

Facility Ranking by Criteria Votes Cast: 21

Votes	Cast: 21 C1: Viability for the capability to			Number of Votes at Each Score (1-5)						
No.	extend our understanding toward accurately simulating nuclear irradiation conditions (neutrons or fission fragments)	Avg. Score	Std. Dev.	0	1	2	3	4	5	
13	University of Michigan – Michigan Ion Beam Laboratory	4.00	0.93	0	0	2	3	9	7	
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.57	0.95	0	0	4	4	10	3	
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.48	0.85	0	0	2	10	6	3	
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.38	1.13	0	1	4	6	6	4	
1	Argonne National Laboratory - Intermediate Voltage Electron Microscope (IVEM)	3.29	0.98	0	1	3	8	7	2	
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.24	0.87	0	0	5	7	8	1	
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.24	0.81	0	0	4	9	7	1	
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.19	1.30	1	2	1	8	6	3	
12	Texas A&M University – Accelerator Laboratory	3.19	1.01	0	2	2	8	8	1	
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.14	0.83	0	2	0	12	7	0	
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.90	0.92	0	1	5	12	1	2	
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.81	0.79	0	2	2	16	0	1	
5	Idaho State University – Idaho Accelerator Laboratory	2.19	0.85	0	5	8	7	1	0	
9	Ohio University – Edwards Accelerator Laboratory	1.90	1.06	2	6	6	6	1	0	
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	1.86	0.99	1	9	3	8	0	0	

	C2: Ability of the facility to provide a			Nun	nber of	Votes a	at Each	Score ((1-5)
No.	variety of ion irradiations (ion types, energies, multiple beams, etc.)	Avg. Score	Std. Dev.	0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	4.10	0.87	0	0	1	4	8	8
12	Texas A&M University – Accelerator Laboratory	3.86	0.89	0	0	1	7	7	6
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.48	1.14	0	1	3	7	5	5
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.43	0.95	0	0	4	7	7	3
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.38	0.84	0	0	3	9	7	2
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.33	1.04	0	1	2	11	3	4
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	3.24	1.02	0	1	3	10	4	3
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.10	1.23	1	0	6	6	5	3
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	3.10	1.11	0	1	7	4	7	2
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.00	1.31	0	3	5	6	3	4
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	2.86	1.21	1	2	3	10	3	2
5	Idaho State University – Idaho Accelerator Laboratory	2.76	1.19	0	4	4	8	3	2
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.67	1.08	1	2	5	8	5	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.10	1.34	1	8	5	4	1	2
9	Ohio University – Edwards Accelerator Laboratory	1.81	1.10	2	8	4	6	1	0

	C3: Ability of the facility to provide a			Number of Votes at Each Score (1-5					
No.	variety of well-controlled target environments and conditions	Avg. Score	Std. Dev.	0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	4.29	0.70	0	0	0	3	9	9
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.48	1.01	0	1	2	7	8	3
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.38	1.05	0	1	3	7	7	3
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.38	0.90	0	1	1	10	7	2
12	Texas A&M University – Accelerator Laboratory	3.33	0.84	0	0	3	10	6	2
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.19	0.85	0	0	5	8	7	1
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.19	0.91	0	1	2	12	4	2
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.19	1.14	0	2	3	8	5	3
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	3.10	0.75	0	0	4	12	4	1
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	2.95	1.05	1	0	5	9	5	1
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.90	0.92	0	1	5	12	1	2
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.76	1.06	1	1	5	10	3	1
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.48	1.01	0	4	7	6	4	0
5	Idaho State University – Idaho Accelerator Laboratory	2.24	1.19	2	3	8	4	4	0
9	Ohio University – Edwards Accelerator Laboratory	1.86	0.99	2	6	6	7	0	0

	C4: Ability of the facility to collect			Number of Votes at Each Score (1-5)						
No.	and analyze materials properties and/or perform microstructural characterization data onsite	Avg. Score	Std Dev	0	1	2	3	4	5	
13	University of Michigan – Michigan Ion Beam Laboratory	3.95	0.79	0	0	0	7	8	6	
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.86	1.21	0	2	0	5	6	8	
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.71	1.12	0	1	2	5	7	6	
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.57	1.00	0	1	1	8	7	4	
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.57	1.18	0	1	3	6	5	6	
12	Texas A&M University – Accelerator Laboratory	3.57	0.95	0	0	2	10	4	5	
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.52	1.05	0	0	5	4	8	4	
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	3.52	1.01	0	0	4	6	7	4	
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.48	1.22	0	1	5	3	7	5	
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.43	1.00	0	0	4	8	5	4	
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	3.19	1.05	0	1	4	9	4	3	
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.10	1.02	0	2	3	8	7	1	
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.71	1.20	1	2	5	9	2	2	
5	Idaho State University – Idaho Accelerator Laboratory	2.24	0.81	0	4	9	7	1	0	
9	Ohio University – Edwards Accelerator Laboratory	1.86	1.04	2	6	7	5	1	0	

	C5: Ability of the facility to collect			Nun	(1-5)				
No.	and analyze materials properties and/or perform microstructural characterization data in situ	Avg. Score	Std. Dev.	0	1	2	3	4	5
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	4.05	1.21	0	1	2	3	4	11
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	4.05	1.29	1	0	1	4	4	11
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.90	1.02	0	1	0	6	7	7
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.67	1.36	0	3	0	6	4	8
13	University of Michigan – Michigan Ion Beam Laboratory	3.52	1.22	1	0	2	7	6	5
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	2.90	1.41	1	4	1	8	4	3
12	Texas A&M University – Accelerator Laboratory	2.90	1.27	2	1	2	9	6	1
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.57	1.53	2	5	2	5	5	2
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	2.48	1.43	2	4	4	6	3	2
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.14	1.25	2	5	5	7	1	1
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	2.10	1.41	4	3	5	6	2	1
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.10	1.31	2	7	3	5	4	0
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.05	1.05	2	4	7	7	1	0
5	Idaho State University – Idaho Accelerator Laboratory	1.29	1.03	6	6	6	3	0	0
9	Ohio University – Edwards Accelerator Laboratory	1.14	0.83	5	9	6	1	0	0

	C6: Current or potential productivity			Number of Votes at Each Score (1-5)					
No.	of the facility (e.g., fewer high-impact experiments or high-volume sample throughput)	Avg. Score	Std. Dev.	0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	3.86	1.08	0	1	0	8	4	8
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.71	1.08	0	0	3	7	4	7
12	Texas A&M University – Accelerator Laboratory	3.48	0.85	0	0	2	10	6	3
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.43	0.73	0	0	1	12	6	2
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.19	1.05	0	1	4	9	4	3
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.10	0.81	0	1	2	13	4	1
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.00	0.93	0	1	5	9	5	1
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP- BLAIRR	2.86	1.12	0	2	7	6	4	2
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.81	0.79	0	1	6	10	4	0
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.76	0.87	0	2	5	10	4	0
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.71	0.88	0	2	6	9	4	0
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	2.67	1.04	0	4	3	11	2	1
5	Idaho State University – Idaho Accelerator Laboratory	2.33	1.13	1	5	4	8	3	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.14	1.21	2	5	4	9	0	1
9	Ohio University – Edwards Accelerator Laboratory	1.86	1.04	2	7	4	8	0	0

	C7: Unique capabilities of the facility,			Number of Votes at Each Score (1-5)					
No.	including any new technology that has the capability to close technological gaps	Avg. Score	Std. Dev.	0	1	2	3	4	5
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.95	0.84	0	0	0	8	6	7
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.90	0.97	0	0	2	5	7	7
13	University of Michigan – Michigan Ion Beam Laboratory	3.76	1.06	0	1	1	6	7	6
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.71	1.03	0	0	3	6	6	6
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.71	0.98	0	0	2	8	5	6
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.48	1.18	0	1	4	5	6	5
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.38	0.90	0	0	4	7	8	2
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.29	1.20	0	2	3	7	5	4
12	Texas A&M University – Accelerator Laboratory	2.95	0.90	0	2	3	10	6	0
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	2.86	0.94	1	0	5	10	5	0
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.67	0.78	0	1	8	9	3	0
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.57	0.79	0	2	7	10	2	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.33	0.89	0	4	8	7	2	0
9	Ohio University – Edwards Accelerator Laboratory	1.95	1.25	3	5	6	4	3	0
5	Idaho State University – Idaho Accelerator Laboratory	1.81	1.01	2	7	5	7	0	0

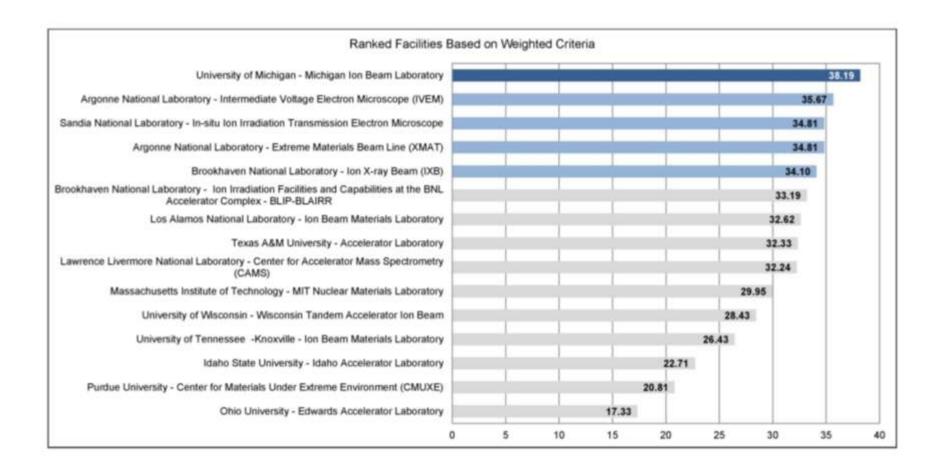
	C8: Ability of the facility to handle			Number of Votes at Each Score (1-5)					
No.	radioactive materials (structural materials and/or fuels) in the beams and elsewhere onsite	Avg. Score	Std. Dev.	0	1	2	3	4	5
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.95	1.00	0	1	1	2	11	6
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.81	1.01	0	1	1	4	10	5
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.62	1.09	0	1	2	6	7	5
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.48	1.10	0	1	2	9	4	5
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.43	1.14	0	1	4	5	7	4
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.29	1.16	0	1	5	6	5	4
5	Idaho State University – Idaho Accelerator Laboratory	3.05	1.05	1	1	1	12	5	1
13	University of Michigan – Michigan Ion Beam Laboratory	2.90	1.27	2	0	3	12	1	3
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	2.62	1.33	1	4	5	4	6	1
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.48	1.14	1	4	3	11	1	1
12	Texas A&M University – Accelerator Laboratory	2.38	0.90	1	2	7	10	1	0
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	2.33	0.94	0	5	6	8	2	0
9	Ohio University – Edwards Accelerator Laboratory	1.29	1.35	8	5	4	3	0	1
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	0.90	0.92	9	6	5	1	0	0
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	0.86	1.12	12	3	3	3	0	0

	C9: Ability of the facility to produce			Number of Votes at Each Score (1-5)					
No.	quality-level data that can support licensing as well as verification and validation of modeling and simulation	Avg. Score	Std. Dev.	0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	3.76	1.02	0	0	3	5	7	6
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.62	0.84	0	0	1	10	6	4
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.62	0.90	0	0	2	8	7	4
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.57	1.40	1	1	2	5	5	7
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.52	1.01	0	1	1	9	6	4
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.43	1.09	0	1	3	7	6	4
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.43	0.90	0	0	3	9	6	3
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.43	1.14	0	2	1	8	6	4
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.33	1.04	0	1	2	11	3	4
12	Texas A&M University – Accelerator Laboratory	3.29	1.20	0	1	5	7	3	5
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	3.05	0.95	0	1	5	8	6	1
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.86	1.21	1	1	6	7	4	2
5	Idaho State University – Idaho Accelerator Laboratory	2.43	0.95	0	4	7	7	3	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	2.24	1.23	1	7	3	6	4	0
9	Ohio University – Edwards Accelerator Laboratory	1.90	1.11	1	9	4	5	2	0

	C10: Ability of the facility to produce			Nun	nber of	Votes	at Each	Score ((1-5)
No.	results that meet the needs of DOE– NE (including cross-cutting programs) and the nuclear energy industry	Avg. Score	Std Dev	0	1	2	3	4	5
13	University of Michigan – Michigan Ion Beam Laboratory	4.05	0.90	0	0	2	2	10	7
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	3.81	1.14	0	1	2	4	7	7
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.67	0.94	0	0	1	11	3	6
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.57	1.09	0	1	2	7	6	5
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.57	1.29	1	0	3	5	6	6
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	3.52	1.18	0	1	3	7	4	6
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.52	1.30	0	3	0	7	5	6
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.52	0.91	0	0	2	10	5	4
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.48	1.22	0	2	2	6	6	5
12	Texas A&M University – Accelerator Laboratory	3.38	1.00	0	1	2	9	6	3
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	3.05	1.33	0	3	5	5	4	4
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.86	1.08	0	3	4	8	5	1
5	Idaho State University – Idaho Accelerator Laboratory	2.38	1.09	1	3	8	5	4	0
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	1.95	1.13	1	9	3	6	2	0
9	Ohio University – Edwards Accelerator Laboratory	1.76	1.23	3	8	3	5	2	0

Overall Facility Rankings

No.	Facility	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Total
13	University of Michigan – Michigan Ion Beam Laboratory	4.00	4.10	4.29	3.95	3.52	3.86	3.76	2.90	3.76	4.05	38.19
1	Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)		3.00	3.38	3.86	4.05	3.71	3.71	3.29	3.57	3.81	35.67
2	Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	3.57	3.10	3.19	3.71	3.90	2.67	3.95	3.62	3.52	3.57	34.81
11	Sandia National Laboratory – In Situ Ion Irradiation Transmission Electron Microscope	3.48	3.43	3.48	3.57	4.05	3.43	3.90	2.33	3.62	3.52	34.81
3	Brookhaven National Laboratory – Ion X-ray Beam (IXB)	3.24	2.86	3.19	3.48	3.67	3.19	3.71	3.48	3.62	3.67	34.10
4	Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex - BLIP-BLAIRR	3.38	3.48	3.19	3.52	2.90	2.86	3.48	3.43	3.43	3.52	33.19
7	Los Alamos National Laboratory – Ion Beam Materials Laboratory	3.14	3.33	3.38	3.57	2.48	3.10	2.86	3.95	3.33	3.48	32.62
12	Texas A&M University – Accelerator Laboratory	3.19	3.86	3.33	3.57	2.90	3.48	2.95	2.38	3.29	3.38	32.33
6	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	3.24	3.38	2.95	3.43	2.10	3.00	3.38	3.81	3.43	3.52	32.24
8	Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	3.19	2.67	2.76	3.10	2.57	2.76	3.29	2.62	3.43	3.57	29.95
15	University of Wisconsin – Wisconsin Tandem Accelerator Ion Beam	2.90	3.10	2.90	3.52	2.14	2.81	2.67	2.48	2.86	3.05	28.43
14	University of Tennessee-Knoxville – Ion Beam Materials Laboratory	2.81	3.24	3.10	3.19	2.05	2.71	2.57	0.86	3.05	2.86	26.43
5	Idaho State University – Idaho Accelerator Laboratory	2.19	2.76	2.24	2.24	1.29	2.33	1.81	3.05	2.43	2.38	22.71
10	Purdue University – Center for Materials Under Extreme Environment (CMUXE)	1.86	2.10	2.48	2.71	2.10	2.14	2.33	0.90	2.24	1.95	20.81
9	Ohio University – Edwards Accelerator Laboratory	1.90	1.81	1.86	1.86	1.14	1.86	1.95	1.29	1.90	1.76	17.33



Community Comments on Facility Rankings

Facilities	Any Comments
Argonne National Laboratory – Intermediate Voltage Electron Microscope (IVEM)	 Comment was made that there should be an "n/a" option in the scoring levels. The IVEM is a clearly an important facility for high-impact science. However, I see no direct linkage between the data emanating from this facility and licensing data. I only see indirect linkage through multi-length-scale modeling.
	3. Ion irradiation data will unlikely be used for licensing purpose without the strong support of computer models to correlate the ion irradiation to neutron irradiation damage. The IVEM-Tandem Facility provides unique capability to facilitate the development of such computer models.
Argonne National Laboratory – Extreme Materials Beam Line (XMAT)	
Brookhaven National Laboratory – Ion X-ray Beam (IXB)	
Brookhaven National Laboratory – Ion Irradiation Facilities and Capabilities at the BNL Accelerator Complex – BLIP-BLAIRR	
Idaho State University – Idaho Accelerator Laboratory	 No in situ capabilities. Lack of in situ capabilities specifically mentioned in the Excel file.
Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (CAMS)	1. No mention of specific in situ capabilities either in the presentation or in the Excel file.
Los Alamos National Laboratory – Ion Beam Materials Laboratory	 These facilities appear duplicative of what is being productively used in the complex. No mention of specific in situ capabilities either in the presentation or in the Excel file.
Massachusetts Institute of Technology – MIT Nuclear Materials Laboratory	1. Entries in the spreadsheet are either not there or statements like "yes." I cannot work with that.
	2. No mention of specific in situ capabilities either in the presentation or in the Excel file. Saying "yes" to the presence of capabilities is not enough.
Ohio University – Edwards Accelerator	1. No info provided on ability to handle radioactive materials.
Laboratory	2. No info provided in the spreadsheet.
	3. Cannot handle radioactive materials.
	4. Ohio can handle 100 mR/hr beta/gamma activity at 25 cm separation.
	5. No mention of specific in situ capabilities either in the presentation or in the Excel file.1. Not able to handle active materials.
Purdue University – Center for Materials Under	1. Not able to handle active materials.

Facilities	Any Comments
Extreme Environment (CMUXE)	2. No info provided on ability to handle radioactive material.
	3. We do not agree with the zero score for Criteria #2, #3, #4, #5, #6, #7, #9, and #10. Someone gave us "zero score" for these criteria, which is certainly NOT true. CMUXE has capability for these criteria, which is self reflected from our presentation slides.
Sandia National Laboratory – In Situ Ion	1. That is BS!
Irradiation Transmission Electron Microscope	2. Assuming that comment refers to the 0 in situ rating. If so, then agreed.
Texas A&M University – Accelerator Laboratory	Apparently not an accurate comment.
University of Michigan – Michigan Ion Beam Laboratory	1. MIBL has the capability to handle 100 mR/hr samples and so should be scored a 3 according to the Criteria Scoring Definitions.
University of Tennessee-Knoxville – Ion Beam	1. Not able to handle active materials.
Materials Laboratory	2. Stated inability to handle radioactive materials.
	3. Cannot handle radioactive material.
	4. Cannot handle radioactive materials.
	5. Cannot handle radioactive materials.
	6. The University of Tennessee has a full suite of materials characterization capabilities onsite, including all the capabilities in the new Joint Institute for Advanced Materials that has opened on campus. We also have all the characterization capabilities available at Oak Ridge National Laboratory.
University of Wisconsin – Wisconsin Tandem	1. We can handle 100 mR/hr on contact—there should be no standard deviation here.
Accelerator Ion Beam	2. UW-Madison supports DOE-NE through a vast number of NEUP projects.
	3. UW-Madison has in situ ion beam analysis (RBS, NRA), in situ chemical analysis through PIXE, and we plan for in situ TEM and molten salt corrosion.

Appendix G Ion Beam Facilities' Quantitative Data

Appendix G

Ion Beam Facilities' Quantitative Data

National Laboratories

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
	Beam #1 Ions	H, He, Li, C, Si, Fe, Ni, Cu, Ag, W, Au, and more	H, He, Ne, Ar, Kr, Xe, and many elements from Al to Au		H, He, B, C, O, Ne, Al, Si, Ti, Cr, Fe, Ni, Au, Ag, etc.
	Beam #1 Energy (Low) (MeV)	0.4	0.05		0.01 He
	Beam #1 Energy (High) (MeV)	21	1		14 (Si)
ristics	Beam #2 Ions	H, He, N, O, Ne, Si, Ar, Fe, Kr, Xe, etc.			
Characteristics	Beam #2 Energy (Low) (MeV)	0.01			
m Ch	Beam #2 Energy (High) (MeV)	0.38			
Bea	Beam #3 Ions				
Situ Ion Beam	Beam #3 Energy (Low) (MeV)				
In Sit	Beam #3 Energy (High) (MeV)				
	Maximum Flux (1E+12 nv)	1E13 ions/cm ² /s	1		
	Maximum Dose Rate (1E-4 dpa/s)	1E-2 dpa/s	1		
	Beam Spot Diameter (mm)	10.0 - 50.0	1.5		

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
	Beam #1 Ions	H, He, Li, C, Si, Fe, Ni, Cu, Ag, W, Au, and more	Не	H, He, and all heavy ions except noble gases	
	Beam #1 Energy (Low) (MeV)	0.4	0.003	1	
	Beam #1 Energy (High) (MeV)	21	0.02	100	
tics	Beam #2 Ions	H, He, Ne, Ar, Kr, Xe, etc.	Heavy ions (e.g., Fe, Ni, Au, Si, etc.)		
Characteristics	Beam #2 Energy (Low) (MeV)	0.01	0.1		
Chara	Beam #2 Energy (High) (MeV)	0.38	4		
Situ Ion Beam	Beam #3 Ions	H, He, Ne, Ar, Kr, Xe, C, Si, Fe, Ni, Cu, Ag, W, Au, and more			
	Beam #3 Energy (Low) (MeV)	0.02			
Ex	Beam #3 Energy (High) (MeV)	0.8			
	Maximum Flux (1E+12 nv)	1E13 ions/cm2/s		10000	
	Maximum Dose Rate (1E-4 dpa/s)	1E-2 dpa/s		100	
	Beam Spot Diameter (mm)	10.0 to 50.0		0.5-10	

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
	Accelerator #1	3 MV NEC Pelletron tandem with radio frequency plasma and sputter ion sources and five beamlines	2 MeV tandem (IVEM)	10 MV FN tandem Pelletron	HVE 6 MV tandem
	Accelerator #2	200 kV Varian DF-3000 ion implanter with gas ion source	500 keV ion implanter (IVEM)	NEC 1.7 MV tandem accelerator	NEC 1 MV tandem
Accelerators	Accelerator #3	200 kV Danfysik high current ion implanter with gas-oven- sputter ion source with potential for up to three beamlines	Low-energy ion gun (IVEM)		NEC 3 MV Pelletron
	Accelerator #4				350 kV High-Voltage Engineering Europa Implanter
	Accelerator #5				A&D 100 kV nanoImplanter
	Accelerator #6				10 kV Colutron
	Accelerator #7				Radio frequency quadrupole booster
	Temperature (Low) (K)	77	20	273 (routine), LN ₂ (possible)	43
	Temperature (High) (K)	1473	1573	1273 (routine), 1473 (possible)	1473
ınt	Air				x
Environment	Gas		Environment cell holder (700°C)		х
nvi	Water				x
	Vacuum	~5E-8 Torr		<2E-7 Torr	~10-7 Torr (normal operation)
	Other	Corrosion experiment chamber and radiation shielding for performing corrosion of lead- bismuth eutectic or molten salts			Liquid cell, gas cell, electrical bias, 77 K to 1000°C

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
	Stage #1	Ion beam analysis chamber (RBS, ERD, NRA, PIXE, and channeling)	Double-tilt low-temperature stage (20–295 K)	Single-tilt general purpose stage (0–1000°C)	Single-tilt, room-temperature straining stage
səğı	Stage #2	High-energy, high-temperature irradiation chamber	Double-tilt, high-temperature stage (20–900°C)	Single-tilt stage for radiological materials (samples over Class III threshold, 0–200°C)	Hysitron PI-95
Specimen Stages	Stage #3	Tandem-Varian dual-beam chamber for damage/He experiments (77 to 1473 K)	Single-tilt, high-temperature stage (20–1300°C)		Double-tilt rotate stage
Spec	Stage #4	High-energy helium implantation chamber	Single-tilt, high-temperature straining stage (20–600°C)		High-tilt (+/- 81) tilt stage
	Stage #5	Irradiation and Corrosion Experiment (ICE) chamber	Single-tilt, low-temperature straining stage (-196–100°C)		2.3-mm heating (800°C) and LN ₂ (77 K) stages
	Stage #6	Low-energy implantation chambers (77–1473 K)			Gas/heating and liquid mixing stages
	TEM	Three TEMs at Electron Microscopy Laboratory	In situ @ IVEM	Ex situ	In situ @ I3TEM
ion	Hardness Testing	Two nanoindenters at the Center for Integrated Nanotechnologies user facility		Ex situ	Quantitative mechanical (Hysitron PI-95)
Characterization	Strain/Tension Testing	In situ strain/tension stage attached to TEMs	- Single-tilt, high-temperature straining stage (20–600°C) - Single-tilt, low-temperature straining stage (-196–100°C)	Ex situ	Quantitative mechanical (Hysitron PI-95 w/P2P)
Ü	X-Ray Techniques	Several x-ray diffraction instruments, including high-temperature grazing incident x-ray diffraction for shallow-depth regions	Ex situ @ Advanced Photon Source	Ex situ	

	Institution	LANL	Argonne National Laboratory	LLNL	Sandia National Laboratories
	Facility	Ion Beam Materials Laboratory	Intermediate Voltage Electron Microscope Tandem User Facility (IVEM-TUF)	Center for Accelerator Mass Spectrometry (CAMS)	In Situ Ion Irradiation Transmission Electron Microscope (I3TEM)
	Fatigue Testing			Ex situ	Quantitative mechanical (Hysitron PI-95 w/P2P) under beta test
	Not Permitted				
	Trace Amount (TEM Lamellae)	Yes	x and 3-mm disk	Yes	Yes
	Contact Direct Reading (DR) Limit (mR/hr)	3000	500		100
	30 cm DR limit (mR/hr)	100	5	100	
eria	Uranium Fuel	X	x	Y	x
Mat	N-Irradiated U Fuel	X	X	Y	x
ve I	Actinides	Depends on activity		Y	
Radioactive Material	Beta-Gamma Activity Limit (Ci)	Isotope specific, e.g., 290 Ci for Co-60		0.005	
Rac	Alpha Activity Limit (Ci)	Isotope specific, e.g., 14.6 Ci for U-235		0.0005	
	Pu-239 Grams Equivalent	38.6 grams		0.5	
	Can Ship and Receive	Yes	@ ANL-IML	Y	Receive
	Radiological Sample Preparation	At nearby Sigma uranium facility and Chemistry Metallurgy Research facility hot cell	@ ANL-IML	Y	

Universities (Texas A&M University, University of Michigan, and University of Wisconsin)

	Institution	Texas A&M University	University of Michigan	University of Wisconsin
	Facility	Accelerator Laboratory	Ion Beam Laboratory	Tandem Accelerator Ion Beam
	Beam #1 Ions	All elements, except heavy noble gases	H, He, D, O, Ar, Ni, Fe, etc.	H, D, He, O, N
	Beam #1 Energy (Low) (MeV)			0.7 MeV
tics	Beam #1 Energy (High) (MeV)	3	>1.5	4 MeV (depends on ion)
Situ Ion Beam Characteristics	Beam #2 Ions	All elements, except heavy noble gases		All sputtered ions if commercial cathode available
har	Beam #2 Energy (Low) (MeV)			0.7 MeV
ı C	Beam #2 Energy (High) (MeV)	1.7	1.2	8.5 MeV (depends on ion)
ean	Beam #3 Ions			
n B	Beam #3 Energy (Low) (MeV)			
l Io	Beam #3 Energy (High) (MeV)			
Sit	Maximum Flux (1E+12 nv)			2e15 ion/cm2/s
In	Maximum Dose Rate (1E-4 dpa/s)		1	1 dpa/s
	Beam Spot Diameter (mm)		2	1–600 mm2
	Beam #1 Ions			H, D, He, O, N
S	Beam #1 Energy (Low) (MeV)			0.7 MeV
risti	Beam #1 Energy (High) (MeV)			4 MeV (depends on ion)
Characteristics	Beam #2 Ions		Zr or Mo	All sputtered ions if commercial cathode available
Ch	Beam #2 Energy (Low) (MeV)			0.7 MeV
	Beam #2 Energy (High) (MeV)			8.5 MeV (depends on ion)
Be	Beam #3 Ions			
Ion	Beam #3 Energy (Low) (MeV)			
itu	Beam #3 Energy (High) (MeV)			
Ex Situ Ion Beam	Maximum Flux (1E+12 nv)			2e15 ion/cm2/s
H	Maximum Dose Rate (1E-4 dpa/s)			1 dpa/s

Universities (Texas A&M University, University of Michigan, and University of Wisconsin) (continued)

	Institution	Texas A&M University	University of Michigan	University of Wisconsin
	Facility	Accelerator Laboratory	Ion Beam Laboratory	Tandem Accelerator Ion Beam
	Beam Spot Diameter (mm)			1–600 mm2
	Accelerator #1	1.7 MV ion accelerator	3 MV tandem (Pelletron) (Wolverine)	1.7 MV tandem
Š	Accelerator #2	3 MV ion accelerator	1.7 MV tandem (Tandetron) (Maize)	
ator	Accelerator #3	400 kV Van de Graaff	0.4 MV implanter (Blue)	
Accelerators	Accelerator #4	140 kV gas atom accelerator		
CCE	Accelerator #5	10 kV gas ion source		
A	Accelerator #6			
	Accelerator #7			
	Temperature (Low) (K)	573 (also LN ₂ temps)	77	77
	Temperature (High) (K)	1073	1500	1500
lent	Air			
nuc	Gas			
Environment	Water		High-temperature/high-pressure water (PWR PW, BWR NWC, BWR HWC)	
	Vacuum	Greater than 2E-7 Torr	10E-8 Torr	1e-8 Torr
	Other			Planned molten salt corrosion
es	Stage #1		High temperature and under static load	
tag	Stage #2			
n S	Stage #3			
ime	Stage #4			
Specimen Stages	Stage #5			
S	Stage #6			
Characterization	TEM			FEI Titan aberration-corrected STEM, Phillips CM200 Ultra Twin TEM, Tecnai T-12 Cryo TEM, Tecnai TF-30
eriz	Hardness Testing		Buehler hardness indenter	Hysitron Tribonanoindenter
ract	Strain/Tension Testing			
Char	X-Ray Techniques		PIXE	Bruker D8 Discovery, PANalytical X'Pert PRO, Rigaku small angle x-ray scattering, Siemens Stoe, PIXE

Universities (Texas A&M University, University of Michigan, and University of Wisconsin) (continued)

	Institution	Texas A&M University	University of Michigan	University of Wisconsin
	Facility	Accelerator Laboratory	Ion Beam Laboratory	Tandem Accelerator Ion Beam
	Fatigue Testing			
	Not Permitted			
	Trace Amount (TEM Lamellae)	x	x	Yes
	Contact DR Limit (mR/hr)	10	100	1000
ial	30cm DR limit (mR/hr)			100
Radioactive Material	Uranium Fuel			Yes
	N-Irradiated U Fuel			Not allowed
	Actinides			Not allowed
	Beta-Gamma Activity Limit (Ci)			0.01
	Alpha Activity Limit (Ci)			Not allowed
	Pu-239 Grams Equivalent			Not allowed
	Can Ship and Receive		@ Michigan Irradiated Materials Testing Complex	Yes, at Characterization Laboratory for Irradiated Materials
	Radiological Sample Preparation			Yes

Universities (University of Tennessee, Idaho State University, Purdue University, and Ohio University)

	Institution	University of Tennessee- Knoxville	Idaho State University	Purdue University	Ohio University
	Facility	Ion Beam Materials Laboratory	Idaho Accelerator Laboratory	Center for Materials Under Extreme Environment (CMUXE)	Edwards Accelerator Laboratory
	Beam #1 Ions	Most elements, except heavy noble gases	Electrons	Inert and some of the reactive gases (H2, CH4, etc.)	
	Beam #1 Energy (Low) (MeV)	0.5	2 MeV	0.0003	
8	Beam #1 Energy (High) (MeV)	27	25 MeV	0.0012	
stic	Beam #2 Ions		Electrons		
acteri	Beam #2 Energy (Low) (MeV)		2 MeV		
Char	Beam #2 Energy (High) (MeV)		44 MeV		
ean	Beam #3 Ions		H,D, others with source		
In Situ Ion Beam Characteristics	Beam #3 Energy (Low) (MeV)		0.5 MeV		
	Beam #3 Energy (High) (MeV)		8 MeV		
	Maximum Flux (1E+12 nv)				
	Maximum Dose Rate (1E-4 dpa/s)	100			
	Beam Spot Diameter (mm)	2 to 5 mm	~10	10	

University of Tennessee, Idaho State University, Purdue University, and Ohio University) (continued)

		University of Tennessee-	y, I tirdue Oniversity, and Omo		
	Institution Facility	Knoxville Ion Beam Materials Laboratory	Idaho State University Idaho Accelerator Laboratory	Purdue University Center for Materials Under Extreme Environment (CMUXE)	Ohio University Edwards Accelerator Laboratory
	Beam #1 Ions				
	Beam #1 Energy (Low) (MeV)				
	Beam #1 Energy (High) (MeV)				
tics	Beam #2 Ions				
acteris	Beam #2 Energy (Low) (MeV)				
Chara	Beam #2 Energy (High) (MeV)				
am	Beam #3 Ions				
Ex Situ Ion Beam Characteristics	Beam #3 Energy (Low) (MeV)				
	Beam #3 Energy (High) (MeV)				
	Maximum Flux (1E+12 nv)				
	Maximum Dose Rate (1E-4 dpa/s)				
	Beam Spot Diameter (mm)				
	Accelerator #1	3.0 MV tandem	25 MeV LINAC		4.5 MV Tandem Van de Graaff
Accelerators	Accelerator #2		44 MeV LINAC		
	Accelerator #3		8 MV Tandem		
	Accelerator #4		45 MV LINAC		
	Accelerator #5		3 MeV pulse power (30kA)		
	Accelerator #6				
	Accelerator #7				

University of Tennessee, Idaho State University, Purdue University, and Ohio University) (continued)

	Institution	University of Tennessee- Knoxville	Idaho State University	Purdue University	Ohio University
	Facility	Ion Beam Materials Laboratory	Idaho Accelerator Laboratory	Center for Materials Under Extreme Environment (CMUXE)	Edwards Accelerator Laboratory
	Temperature (Low) (K)	25	298		
ent	Temperature (High) (K)	1475			
Environment	Air				
nvir	Gas				
ᅙ	Water				
	Vacuum	High vacuum	High vacuum available		
	Other				
Sa	Stage #1				
age	Stage #2				
n S	Stage #3				
ime	Stage #4				
Specimen Stages	Stage #5				
S	Stage #6				
	TEM		x		
Characteriza- tion	Hardness Testing				
	Strain/Tension Testing				
	X-Ray Techniques				
	Fatigue Testing				

University of Tennessee, Idaho State University, Purdue University, and Ohio University) (continued)

	Institution	University of Tennessee- Knoxville	Idaho State University	Purdue University	Ohio University
	Facility	Ion Beam Materials Laboratory	Idaho Accelerator Laboratory	Center for Materials Under Extreme Environment (CMUXE)	Edwards Accelerator Laboratory
	Not Permitted	X			
	Trace Amount (TEM Lamellae)		X		
	Contact DR Limit (mR/hr)		100		
	30-cm DR limit (mR/hr)				
al	Uranium Fuel				
Radioactive Material	N-Irradiated U Fuel				
	Actinides				
	Beta-Gamma Activity Limit (Ci)				
	Alpha Activity Limit (Ci)				
	Pu-239 Grams Equivalent				
	Can Ship and Receive		Hot lab for radiochemistry and an SEM/TEM/FIB lab that can handle moderate activity material		
	Radiological Sample Preparation				

